Independent Review of the Proposed Closure of the Glenn Research Center (GRC) Altitude Combustion Stand (ACS) and Research Combustion Laboratory Cell 32 (RCL–32) Facilities

November 10, 2010

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Volume I: Technical Assessment Report

1.0 Notification and Authorization

Mr. Ray Lugo, the *then* Acting Center Director at Glenn Research Center (GRC) requested an independent review of the proposed Space Operations Mission Directorate (SOMD) fiscal year (FY) 2012 Program and Resources Guidance (PRG) decision to close and demolish the Altitude Combustion Stand (ACS) and the Research Combustion Laboratory Cell 32 (RCL-32) at the Glenn Research Center (GRC), and transfer the Propulsion and Cryogenic Advanced Development (PCAD) Project's liquid oxygen/methane (LO2/CH4) development testing to the Johnson Space Center (JSC)-White Sands Test Facility (WSTF).

A NASA Engineering and Safety Center (NESC) out-of-board activity was approved July 1, 2010. Mr. Steve Minute, NESC Chief Engineer at the Kennedy Space Center (KSC), was assigned to provide an independent technical team with relevant expertise to assess the proposed PRG decision to close and demolish the ACS and RCL-32 facilities, and transfer PCAD development testing to JSC-WSTF. An assessment plan was approved by the NESC Review Board (NRB) on July 8, 2010. The final report was approved by the NRB on November 10, 2010.

The key stakeholders for this assessment are Mr. Ray Lugo, the *current* GRC Center Director; Mr. Bill Gerstenmaier, Associate Administration (AA) Space Operations Mission Directorate (SOMD); Mr. Doug Cook, AA, Exploration Systems Mission Directorate (ESMD); Dr. Woodrow Whitlow, AA, Mission Support Directorate (MSD); Mr. Michael Coats, JSC Center Director; Mr. Frank Benz, JSC-WSTF Facility Manager; Mr. Bobby Braun, Chief Technologist; and Mr. Roger Simpson, Program Manager, Rocket Propulsion Test Program.

2.0 Signature Page

Submitted by:

Mr. Steve Minute Date

Significant Contributors:

Mr. Chris Chromik Date

Mr. Hamilton Fernandez Date

Mr. Robert Garcia Date

Mr. Steve Gentz Date

Mr. Michael Squire Date

Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

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Core Team		
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3.1 Acknowledgements

The team would like to acknowledge and thank the following individuals for their assistance in this assessment: Roger Simpson, Rocket Propulsion Test (RPT) Program Manager, and Wei Yen Hu, Technical Capabilities and Real Property Management Division.

GRC

The team would like to acknowledge and thank the personnel from GRC for their assistance in providing requested materials and information, and for giving the team a tour of the RCL facilities. The following GRC individuals were instrumental in the completion of this assessment: John Schubert, Lynn Arrington, Anita Liang, Mark Klem (PCAD), Bruce Rosenthal, Harry Cikanek, and Desa Rakic.

JSC-WSTF

The team would like to acknowledge and thank the personnel from JSC-WSTF for their assistance in: the various technical discussions; making available the requested materials and information; and for providing a tour of Test Area 400 including Test Stand (TS) 401, 403, 405, and 406, and the Small and Large Altitude Simulation Systems (SASS and LASS). The following JSC-WSTF individuals were instrumental in the completion of this assessment: Mike Owen, Bob Kowalski, Kevin Farrah, and David Baker.

4.0 Executive Summary

On June 7, 2010 the *then* Acting Director of Glenn Research Center (GRC), Mr. Ramon (Ray) Lugo, expressed a concern regarding the proposed Program and Resources Guidance (PRG) decision to close and demolish the Altitude Combustion Stand (ACS) and the Research Combustion Lab - Cell 32 (RCL-32) at GRC, and transfer the Propulsion and Cryogenic Advanced Development (PCAD) liquid oxygen/liquid methane (LO2/LCH4) development testing to the Johnson Space Center (JSC)-White Sands Test Facility (WSTF). Mr. Lugo requested the NESC perform an independent review of these decisions. The request was to assess the requirements versus capability as well as a rough order of magnitude (ROM) cost estimate of both recurring and non-recurring costs for testing in the subject GRC and JSC-WSTF facilities. In mid-July the NESC requested support from the Independent Program Assessment Office (IPAO) to assess the non-recurring and recurring costs at both NASA locations.

The facility related cost and technical assessment was based on site visits and a review of pertinent technical and programmatic documents along with interviews with appropriate key personnel from GRC and JSC-WSTF. The documents reviewed included the Space Operations Mission Directorate (SOMD) Program Planning Budget Execution (PPBE) PRG report, historical cost data, facility studies, technical documents, and previous assessments. The interviews were conducted with technical experts, study leads, project management personnel, and cost estimators.

The NESC assessment approach was to divide the tasks according to team member expertise. Team members familiar with GRC concentrated on identifying the requirements and capabilities at that facility, while other members familiar with JSC-WSTF followed a similar approach. The team members familiar with testing at both locations compared and contrasted the requirements and capabilities. The team members from IPAO were primarily responsible for evaluating and validating the recurring and non-recurring test and facility cost estimates.

The assessment team outbriefed the findings, observations and NESC recommendations to the requester and stakeholders on (*Fill in Date*). There were eleven findings, nine observations, and four recommendations.

The NESC team did not identify any technical reason why current LO2/LCH4 testing at GRC ACS or RCL-32 could not be relocated to JSC-WSTF. However, cost risks associated with demolition of the GRC facilities suggests that demolition at this time would be premature, and from a system reliability standpoint, the Rocket Propulsion Test (RPT) Program identified there is moderate likelihood that the JSC-WSTF Large Altitude Steam System (LASS) could become inoperable during an engine firing because of age-related degradation. The result could be data loss, delay in testing, and/or hardware damage for engine testing greater than approximately 1,000 pound force (lbf).

In considering cost risks, the PRG recommendation to demolish ACS and RCL-32 does not appear to be a prudent decision at this time for the Agency. Although ACS, RCL-32, TS 401, and TS 403 have historically been underutilized, the future Agency needs are not well understood. In addition, the costs of demolition have not been assessed in the PRG recommendation (estimated at \$3M - \$5M). RCL-32 shares a common blast wall and ceiling with an adjacent sea-level test cell that would make demolition impractical. Also, there are numerous supporting systems and utilities interconnected with ACS, RCL-32, and the other RCL test areas that need to be considered in the decision to demolish the ACS and RCL-32 facilities.

In addition to the estimated demolition costs at GRC, there are several other recurring and non-recurring cost risks associated with JSC-WSTF testing that require deliberation. Additional recurring cost risks could be \$350K or more per year for maintenance, higher JSC-WSTF testing costs and GRC personnel travel costs. Non-recurring cost risks (primarily attributed to capital upgrades, Department of Defense (DOD) Minuteman testing relocation, and propellant conditioning and feed systems (PCFS) relocation) could range from \$800K to \$3M.

In general, the NESC team finds that there are unique capabilities available at ACS and RCL-32 at GRC that are not available at TS 401 at JSC-WSTF. These include GO2/GH2 capability and higher LO2/LH2 propellant pressures. These capabilities coupled with the CH4 capability provide a unique redundancy between ACS/RCL-32 and TS 401. Additionally, ACS appears to be a unique national capability with its LO2/LH2 pressures at altitude.

After extensive data review and personnel interviews, and in consideration of the Agency uncertainties with respect to the development of low to midrange thrust (i.e., 2,000 to 25,000 lbf) cryogenic engines, the NESC recommends the GRC ACS and RCL-32 test capabilities should be retained until the RPT Program updates the Agency’s current and projected need for domestics cryogenic engine testing in the 2,000 lbf and less thrust range.

5.0 Assessment Plan

The objective of this assessment was to review the proposed PRG decision to close and demolish the ACS and RCL-32 at GRC and transfer PCAD LO2/LCH4 engine testing to JSC-WSTF. The NESC team approach was to assess the following:

1. Current requirements and capabilities at both engine test locations.
2. Future requirements and capabilities at both engine test locations.
3. ROM estimates of recurring and non-recurring cost at both locations.

The cost and technical assessment was based on site visits and a review of pertinent technical and programmatic documents along with interviews with appropriate key personnel from GRC and JSC-WSTF. The documents reviewed included the Space Operations Mission Directorate (SOMD) Program Planning Budget Execution (PPBE) PRG report, historical cost data, facility studies, technical documents, and previous assessments. The interviews were conducted with technical experts, study leads, project management personnel, and cost estimators. This assessment was performed in conjunction with a technical cost assessment team from the IPAO. Due to the uncertainty of the NASA budget and the Constellation Program (CxP), future requirements could not be assessed with sufficient certainty. A list of the documentation and references that were reviewed is located in Section 15.0 and the report Appendices.

The NESC teams' approach was to divide the effort according to the team member expertise. Team members familiar with GRC concentrated on identifying the requirements and capabilities of ACS and RCL-32, while other members familiar with JSC-WSTF concentrated on the requirements at this location. Interviews with personnel at GRC and JSC-WSTF were conducted as well as site visits to both facilities by both groups. The team members familiar with testing at both locations compared and contrasted the requirements and capabilities. The members of the team from IPAO were primarily responsible for evaluating and validating the recurring and non-recurring cost estimates at both locations.

The assessment team out-briefed the findings, observations, and NESC recommendations to the requester and stakeholders on (*Fill in Date*). The stakeholder outbrief presentation is located in Appendix L. This final report provides findings, observations, and NESC recommendations, which were based on the material available during the assessment period from June 21 to October 21, 2010.

6.0 Altitude Stand Introduction

The performance of a rocket chemical propulsion system is affected by the environment in which it operates; most notably the surrounding pressure and temperature. In particular, the ambient backpressure has a major impact on the preparation for hot-fire, ignition, and the steady state performance of a conventional chemical rocket engine. Propulsion systems utilizing cryogenic propellants often require a "chilldown" period prior to ignition. This period is needed to achieve proper clearances between moving parts (which change as the parts are cooled to the propellant temperatures) and to achieve proper propellant conditions (i.e., temperature and pressure) necessary for engine operation. Chilldown requires venting to remove the gas that is formed when the cold cryogenic propellants first encounter the ambient temperature propulsion system parts. The approach also typically requires drains that allow propellant to be expelled from the system so that conditioned cryogens can be introduced throughout the chilldown process. The engine characteristics during chilldown will be affected by the ambient pressure since these vents and drains typically are on-off devices.

Reliable rocket engine ignition requires precise control of the propellant flow ramp from zero thrust to the desired steady state level. In the case of non-hypergolic propellants, ignition also requires the application of an external energy source to begin the combustion process. Propellants do not readily combust in their liquid state, but rather in their gas state. Liquid propellants must be vaporized prior to combustion. During normal operations the vaporization of propellant entering the combustion chamber is accomplished by heat addition from the combustion already underway in the chamber. However, during ignition a substantial percent of vapors can be formed from a drop in pressure of the propellants entering the combustion chamber. Therefore, the absolute chamber pressure prior to the engine start command will affect the reliability of the ignition process, and its severity on the chamber materials (e.g., temperature spikes, pressure oscillations). Validation of the ignition system for an engine requires proper simulation of the pressure to be experienced during flight operations.

The pressure at the engine nozzle exit affects the amount of thrust produced, the difference between nozzle exit and ambient pressure times the nozzle exit area being one source of thrust generation. Additionally, the ambient pressure will often limit the area ratio that can be achieved with a bell nozzle. To achieve high specific impulse, the largest practical nozzle area ratio is desirable. However, for a given chamber pressure, if the nozzle area ratio is too large for the ambient pressure, then the flow in the nozzle will separate. This separation will generally result in large unsteady loads, which can lead to engine failure. Therefore, an engine designed to operate with low ambient pressures cannot be readily tested at sea level[1] conditions without making some compromise in the testing (i.e., by testing with a truncated nozzle).

[1] Sea level for the purposes of this report constitutes the local ambient atmospheric pressure located at GRC or JSC-WSTF)

The ambient pressure, and corresponding density, also affects the rate at which heat can be removed from the combustion chamber and nozzle. For components that have regenerative cooling, the external conditions do not significantly affect cooling effectiveness. However, for components that rely on radiative cooling, the ambient conditions will have a marked effect. To validate the design, it is important to be able to test the engine in conditions where the ambient density, and therefore pressure, is representative of the operational value to the extent possible.

Validation of performance of an engine optimized to operate under low ambient pressures requires a facility that can create a localized low pressure environment around the engine even as it expels hot, high velocity exhaust. This type of facility is referred to an altitude test facility. These facilities can achieve and maintain pressures on the order of 0.2 pounds per square inch absolute (psia) while the engine is operating. It can be seen in Figure 6.0-1 that this pressure corresponds to an altitude of approximately 95 thousand feet (Kft).

Lower pressures are achievable in vacuum chambers and are important for testing of other space systems. However, for a rocket engine further reduction in pressure beyond a simulated altitude of 95 to 100 Kft is rarely required. An altitude test facility will often utilize vacuum pumps to lower the pressure in the test cell prior to engine operation. Vacuum pumps are an efficient and economical way to achieve low pressures as long as the volumetric flow of gas being added to the test cell is relatively low or the test chamber is relatively large. The GRC and JSC-WSTF altitude test facilities under review for this assessment can utilize vacuum pumps to prepare the test cell for an engine test and to maintain vacuum conditions between tests while the engine is not operating. As the volumetric flow increases, for example due to engine operation, it is often necessary to employ an ejector system to maintain the desired test cell pressure.

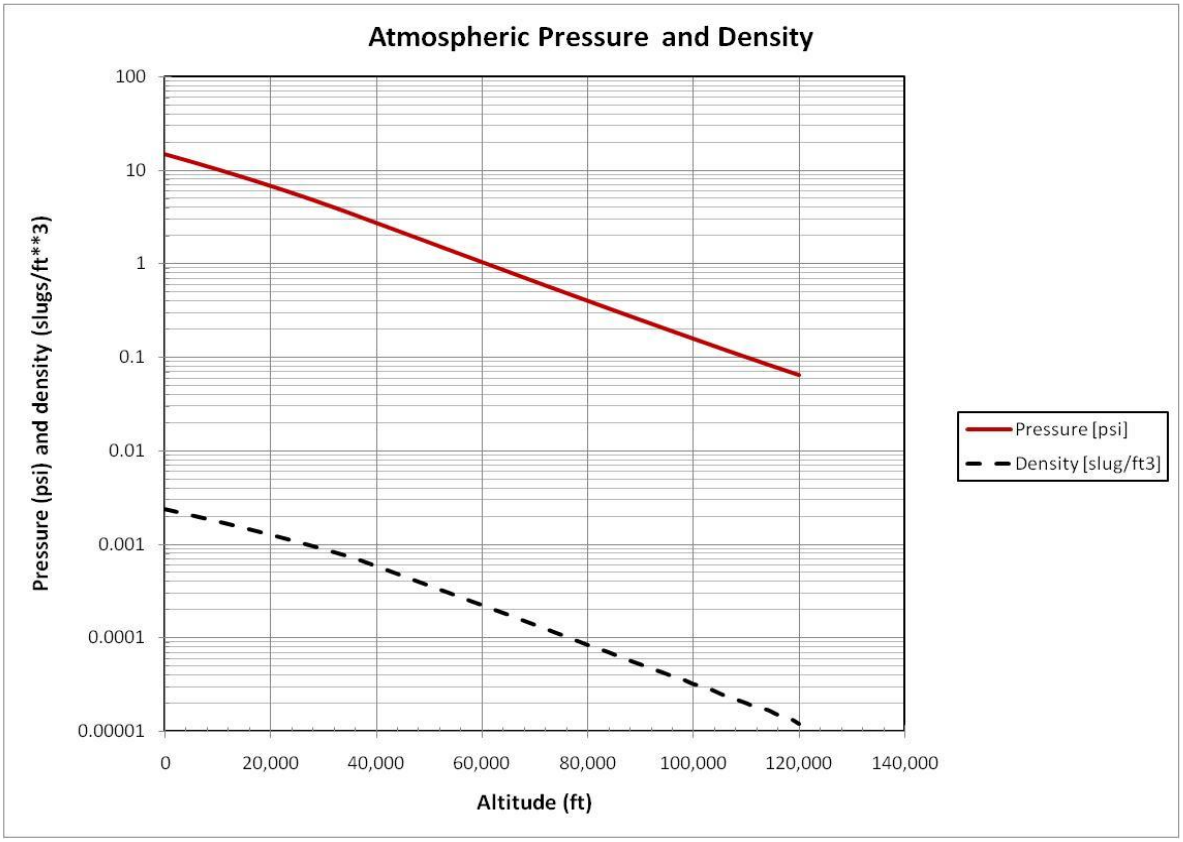

Figure 6.0-1. Pressure and Density Variation with Altitude [ref. 9]

An ejector system utilizes a facility provided source of high pressure gas (typically gaseous nitrogen (GN2) or steam) that is introduced into the test chamber at high speeds. This secondary gas flow is introduced upstream of a geometric constriction and creates a low pressure, supersonic flow region that maintains the reduced pressure in the test cell. When the test engine is operating, engine exhaust mixes with the ejector system gas, which aids in lowering the test cell pressure. For a given ejector design, if the engine flow rate exceeds the ejector's ability to "swallow" the flow, the ejector system will experience a series of weak (oblique) shocks slowing the combined ejector and engine flow relatively strong (normal) shock forms in the exhaust duct, leading to a rapid pressure increase in the test cell (called un-start). This un-start often results in damage to the engine and the test cell. Therefore, a given ejector system has an operating envelope that spans from the pressure it can achieve when operating without the aid of the test engine, to how much volumetric flow it can tolerate before un-starting. To increase the test cell range of operation, a facility can employ ejectors in series. Typically no more than two are used in series, with each additional ejector typically having a reduced impact on the minimum achievable pressure.

The ACS test chamber can operate with either a single ejector train or with two ejector trains in parallel, depending on the test needs. Since both ejector trains are powered by the same high pressure GN2 supply, when operating with both ejector trains, the maximum test run time is significantly reduced. The JSC-WSTF Test Stand (TS) 401 in addition to vacuum pumps and blowers utilizes a two-stage ejector system running from two separate sources (LASS/SASS). One source comes from boilers that use diesel fuel to heat water into steam. This powers the small altitude simulation system (SASS). The other source, the LASS, uses oxygen (O2) and alcohol burners, into which is added water spray, to create mixture of steam and combustion products. The LASS has three burners (Figure 6.0-2) available for generating the ejector gas.

Figure 6.0-2. LASS Steam Generators

Altitude test facilities often use cooling water, sprayed into the exhaust flow, to aid exhaust gas pumping by cooling the exhaust gas, condensing water vapor, and, therefore, reducing the overall volumetric flow downstream of the throat. This can also be necessary to reduce the amount of pollutants, as the water will tend to reduce the percent of particulates in the exhaust gas. Finally, the water spray may also be necessary to cool the walls of the test duct, especially in areas where the hot exhaust flow is being turned to accommodate geometry limitations or to safely direct the exhaust gas in the desired direction.

7.0 Site Information: Reviews, Analysis, and Discussions

7.1 GRC ACS and RCL-32 Test Facilities

7.1.1 Facility Description

GRC has a long history of propulsion research, development, and testing that began with the founding of the Center in the 1940's. The current GRC rocket engine propulsion testing is performed at the RCL (Figure 7.1-1) and at the Plum Brook Station in Sandusky, Ohio. The facilities at Plum Brook Station are used for large or full-scale engines that generate up to 100,000 lbf of thrust, while those at the RCL are for smaller and/or developmental test articles with stands capable of testing engines that generate up to 2,000 lbf of thrust. The facilities under review for this activity, the ACS and the RCL-32 test stand, are located at the RCL (Figure 7.1-2). The 1940's-era RCL complex houses several test stands for altitude and sea level engine testing, using shared facilities and safety systems. Also located at the RCL are two fuel cell test stands, and a heated tube facility, to study heat transport properties of propellants. GRC also includes a large engineering organization, which constitute some of the users for the RCL facilities. These users benefit from onsite testing facilities collocated with their offices, laboratories, and other ancillary facilities.

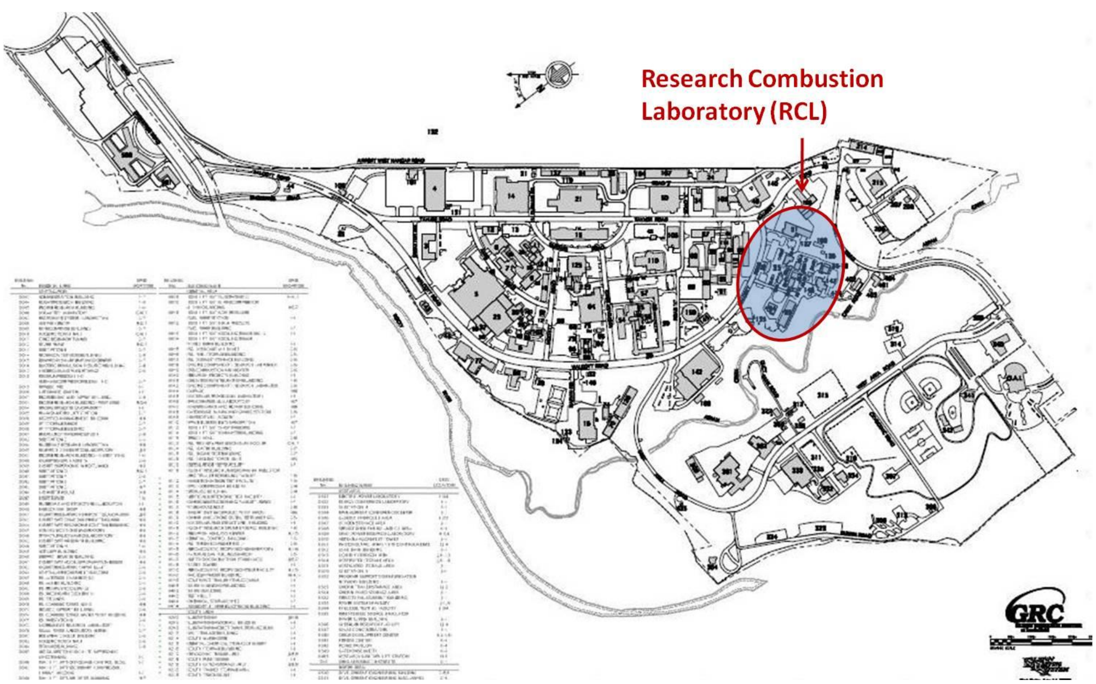

Figure 7.1-1. GRC Campus Map Showing RCL Location

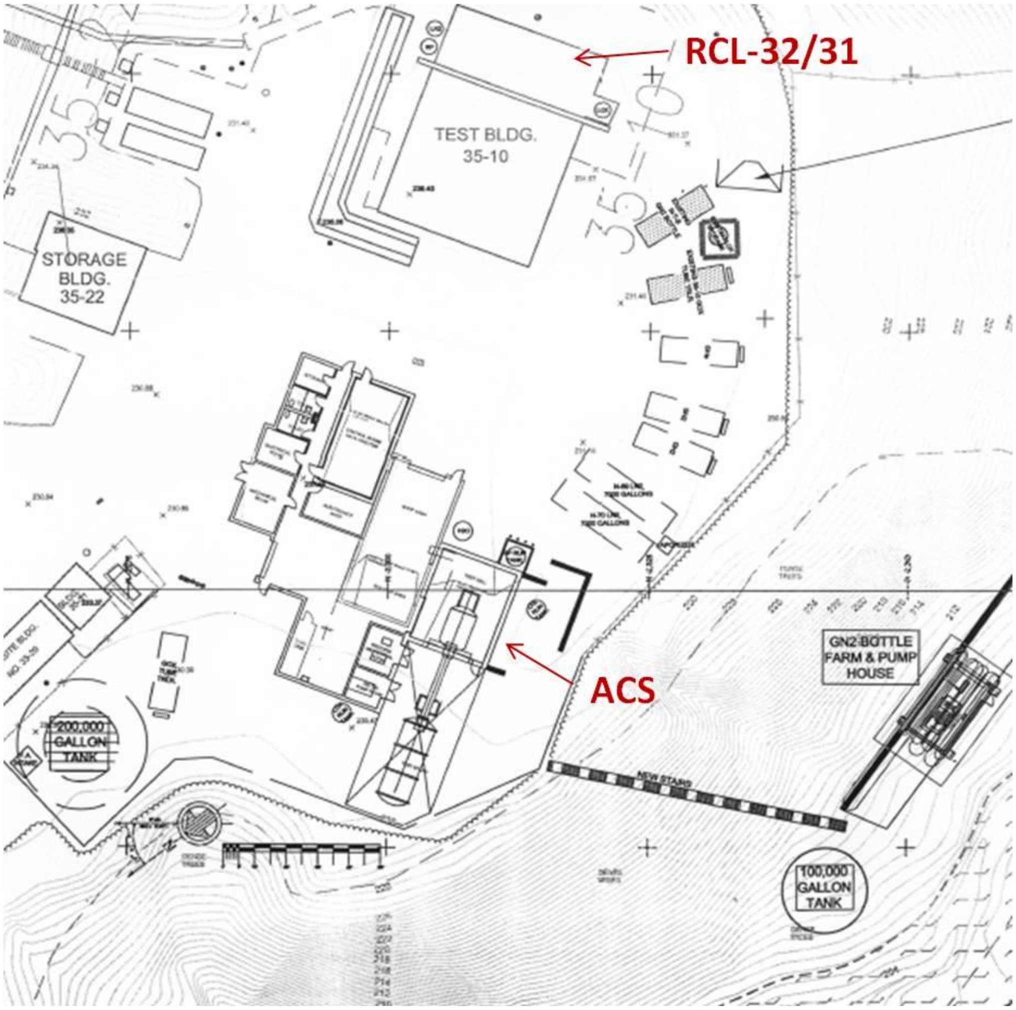

Figure 7.1-2. Relative Location of the ACS and RCL-32

7.1.2 ACS

The predecessor to the ACS was the B-stand test facility. The B-stand was built in 1985 as part of the Rocket Engine Test Facility. In the 1997, GRC and the city of Cleveland entered into an agreement where in exchange for 40 acres of NASA property, the city of Cleveland would fund the relocation of the facilities (B-stand) that were on that land at the time. The property in question would be used in the expansion of Cleveland's Hopkins International Airport. The airport expansion took place in the late 1990's, and B-stand was dismantled and stored. ACS construction began in 2007. Many of the large components from the B-stand, including the vacuum capsule and a number of the structural members, were used in the construction of the ACS. No NASA safety waivers or violations were encountered in the construction of this facility. The exterior of the ACS is seen in Figure 7.1-3.

The ACS is located in Building 147. This facility is a mid-range, altitude test facility. The maximum engine thrust for this stand is 2,000 lbf at altitude, and the maximum chamber pressure is 1,000 psia based on supply pressure limitations. Table 7.1-1 provides a summary of ACS capabilities. Sea level testing can be performed at the ACS without damage to the facility, but the sea level maximum thrust is limited to less than 2,000 lbf. The ACS was designed for testing of components and small engines undergoing development. The facility is equipped with an axial thrust stand, and gaseous and cryogenic propulsion delivery systems. A GN2 ejector system with a 33 inch diffuser is used to simulate low pressure/high altitude conditions. The vacuum capsule has an inner diameter of approximately 8 ft and an inner length of approximately 12 ft. Adjacent to the diffuser is a water spray chamber used to arrest and cool the engine exhaust. The ACS has a dedicated state-of-the-art (circa 2007) data acquisition and control system (DACS). Like all of the test stands in the RCL, the ACS is not rated for hypergolic or toxic propellant testing.

Figure 7.1-3. Exterior of the ACS showing the Vacuum Capsule, Water Spray Chamber and the GN2 Ejector Trains

System activation testing of the ACS was initiated in March 2009 with hydrogen (H2) and O2 propellants. The ACS became operational in November 2009 when PCAD commenced testing the 100 lbf reaction control engine (RCE) as shown in Figure 7.1-4. PCAD's RCE testing has been the only customer for the ACS since it became operational, and will be until the end of the 2010 fiscal year (FY). Beyond that time, there have been no identified users for the ACS. Based on PCAD's 100 lbf test experience costs were $146K/month for the ACS. Standby costs for the ACS are $15K/month. The ACS requires four to five people to run the facility during testing, not including the investigators/users.

Table 7.1-1. ACS Test Chamber Summary

Firing Orientation	Horizontal, axial thrust
Number of Positions	1
Maximum Thrust (lbf)	2,000
Maximum Rocket Chamber Pressure (psia)*	1,000
Engine Firing Maximum Altitude (Kft)	Up to 130 in optimal conditions
Diffuser Diameter (inch)	33

*Note: 1,000 psia is chosen to ensure the system retains adequate control authority. If the test article combined with the test stand configuration can accommodate, there is no restriction against exceeding 1,000 psia if conditions necessary.

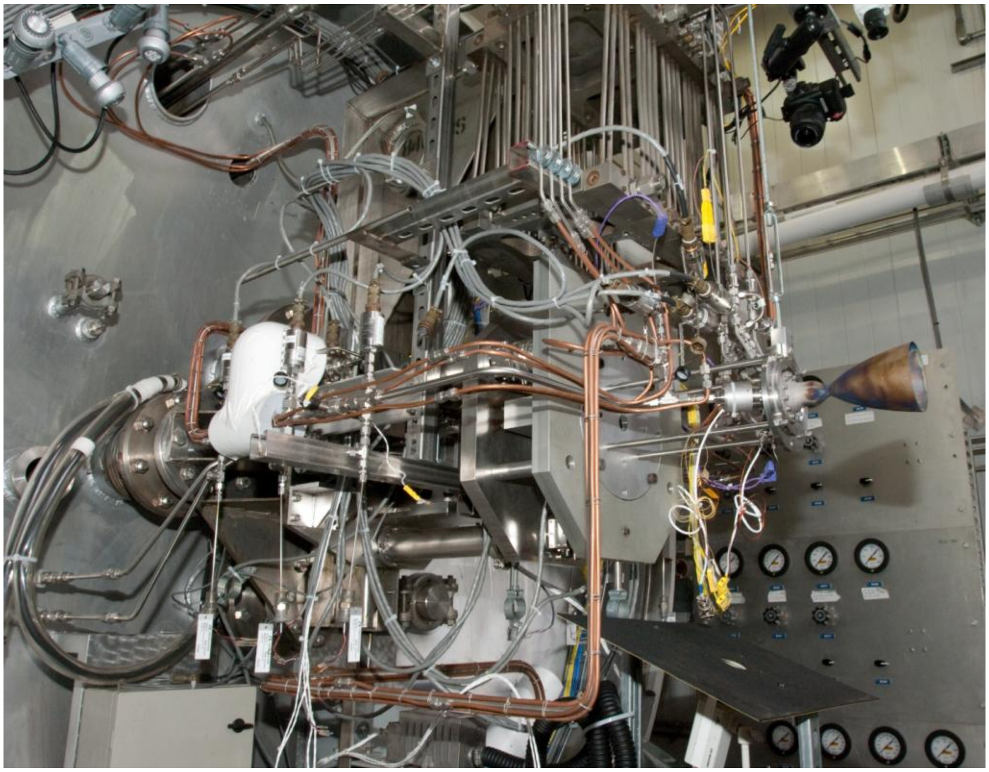

Figure 7.1-4. ACS Test Stand with 100 lbf RCE Test Article

The current ACS propellant capability is shown in Table 7.1-2. Other non-toxic hydrocarbon propellants (e.g., ethanol) not shown in the table can be accommodated with modifications to the test stand. Water can also be used as a propellant medium. Conditioning of LO2 and LCH4 is achieved with the PCFS provided by the PCAD Project. Water used in the spray chamber is supplied from the RCL's 200,000 gallon tower and discharged into 80,000 gallon retention tank. The water tower is filled with city water, and flows at a maximum of 12,000 gal/min into the spray chamber. ACS tests are time-limited by the ejector run-time and not the water supply.

Table 7.1-2. ACS Propellants Summary

Propellant	Volume	Pressure (psi)	Flow Rate (lbm/sec)	Inlet Conditioning (R)
LH2	200 gal	1,800	1.5	N/A
GH2	140,000 scf	2,400	3	N/A
LO2 (unconditioned)	200 gal	1,800	7	N/A
LO2 (conditioned)	60 gal	525	0.5	145 to 243 (+/- 5 deg)
GO2	60,000 scf	2,400	7	N/A
LCH4 (conditioned)	60 gal	525	0.16	170 to 304 (+/- 5 deg)
RP-1	100 gal	1,800	2.65	N/A

Several infrastructure networks interface with the ACS. The ACS is connected serially to the natural gas, electrical power, and storm water containment networks, so that these systems route through the ACS complex and subsequently to other buildings. Other institutional systems tie-in with the ACS on the perimeter, and would be less impacted if the ACS were removed. These systems include the domestic water and waste (sanitary sewer and industrial waste) systems. Similarly, the ACS is the end of the supply line and therefore has a single interface point for the service air, telephone, fire protection, and computer systems. The ACS liquid nitrogen (LN2) dewars, vaporizers and pumps are also used by the RCL, and the ACS liquid argon dewar supplies this cryogen to RCL-31/32.

O-1. The demolition of the ACS facility and infrastructure would incur collateral impacts to other GRC operations.

Altitude Simulation System

The altitude simulation system for the ACS uses a two-stage GN2 ejector system augmented by service air ejectors and mechanical vacuum pumps. The nominal altitude simulation achievable is approximately 100 Kft, but can reach up to 130 Kft under optimal weather conditions (colder ambient temperatures allow for higher simulated altitudes). Two ejector trains are available for testing: Ejector Train 1 with a usage rate of 45 lb/sec, and Ejector Train 2 with a usage rate of 23 lb/sec. A third ejector train is used only for pre-test chamber evacuation. The ejectors flow through a 33 inch diameter diffuser, which is housed inside the 8 by 14 foot vacuum chamber (the diffuser is shown in Figure 7.1-5). Prior to the start of a test series, the vacuum chamber is evacuated using either a service air-fed ejector train, a GN2-fed ejector train (Ejector Train 3), or a mechanical vacuum pump. This initial evacuation process is completed in approximately 20 to 30 minutes. The service air or GN2 systems may be adequate to obtain the required vacuum level on the test article, and the larger ejector trains may not be required if the combination of thrust level and chamber pressure are at a small enough scale. Much of the engine testing at the ACS consists of short-duration firings on the order of 10 seconds. Continuous utilization of the ejectors would discharge the GN2 supply in approximately 3 minutes for a 2,000 lbf engine, and 10 minutes for a 100 lbf engine. Subsequent recharging of the GN2 bottle farm from the on-site LN2 dewars and vaporizers requires approximately 2 to 3 hours. If additional runtime were required, the system is scarred to receive additional GN2 supply bottles. The by-products of the ACS during operation are only GN2 from the ejectors, water from the spray system, and the combustion products from the engine being tested. These waste products, especially from the ejectors, are relatively clean and environmentally sound.

Figure 7.1-5. ACS Diffuser (Ejector Trains 1 and 2 are Visible in the Background)

ACS Instrumentation and DACS

The instrumentation capability is configurable dependent on the user's requirements. This section summarizes the instrumentation and DACS capability and associated accuracies. All of the instrumentation and DACS represent equipment installed since 2007. See Figure 7.1-6 for a view of the dedicated ACS control room.

Figure 7.1-6. ACS Control Room

Strain Gauge Pressure Transducers and Load Cells

The ACS has approximately 140 dedicated strain gauge pressure transducers (gauge, absolute, and differential) and associated signal conditioning with ranges from 1 pound per square inch differential (psid) to 3,000 pounds per square inch gage (psig). Transducer accuracies are ± 0.25 percent full-scale. Also included with the ACS are custom strain gauge load cells mounted in the test engine thrust stand. The load cells have rated accuracies of ± 0.05 percent.

Temperature Instrumentation

The ACS has approximately 150 channels available for thermocouple measurements. Thermocouple accuracies are based on the alloy type and range of temperature measurement but typically type T has an accuracy of +/-0.75 percent over the positive range or +/-1.5 percent below 492 R, type K has an accuracy of +/-0.75 percent over the positive range or +/-1.5 percent below 492 R, and type E has an accuracy of +/-0.5 percent over the positive temperature range or +/-2 percent below 492 R. In addition, the ACS has provisions for 16 silicon diode sensors and the associated constant current excitation signal conditioning for measuring cryogenic temperatures and/or liquid level detection in tanks and vessels. Temperature accuracies for the types of diodes used are generally ± 0.25 percent in the range 4 to 180 R, and ± 1 percent in the range 180 to 855 R. Resistive temperature devices (RTDs) are also supported by the temperature signal conditioning system. Provisions for platinum RTDs and associated signal conditioning for measuring cryogenic temperatures are also supported by the facility. Typical accuracies for class B RTDs range from +/-1.3 R at 132 R, +/-0.3R at 492 R, and +/- 2.8 R at 392 R.

Flow Rate Instrumentation

The ACS contains multiple dual rotor turbine flow meters with integrated flow computers for measuring flow rates in H_2, CH_4, and O_2 systems. The flow meter accuracy is listed as ± 0.1 percent.

Cameras

Eight explosion-proof camera's are in place for monitoring facility operations. Each camera has remote pan, tilt, and zoom functions, and is recorded on digital media. Inside the ACS vacuum chamber are three additional fixed position color charge coupled device (CCD) cameras, and one 35 mm single-lens reflex (SLR) remotely-controlled digital camera for recording test hardware activities.

DACS

The digital DACS displays and records facility/test-specific instrumentation. The total capacity of the DACS is approximately 400 data channels. The data acquisition signal conditioning hardware can accommodate 200 channels of strain gauge inputs, 150 channels of thermocouple or voltage type input signals, and the remainder as frequency-to-voltage and multiple voltage level inputs. Anti-aliasing filters are also installed in the signal conditioning paths. The nominal scan rate is 1 kHz, but is variable and based upon channel count and conversion type. A programmable logic controller (PLC) is used to control the facility and research test hardware inputs and outputs, which is accomplished through a separate system from the data acquisition system. Approximately up to 400 analog and discrete inputs and 200 analog and discrete outputs can be monitored and controlled. A graphical human machine interface (HMI) serves as the interface for operator input and display.

PCFS

The PCFS were not part of the original ACS design, and were supplied by PCAD for testing of their 100 lbf RCE. They are portable, but their dimensions of 10 by 10 by 12 feet and weight of approximately 10,000 pounds (lbs) must be considered when contemplating relocation. The PCFS consists of 1 LO2 and 1 LCH4 conditioning unit (Figures 7.1-7 and 7.1-8). The two units are essentially of the same general design, with the major difference a cryogenic submersible pump system on the LCH4 skid. The skids were designed to provide propellants at set temperatures to the test article inlet. Per design, the system can condition the propellants within one hour to a temperature ± 5 R of the set point. The design and operation of the PCFS was optimized for the ACS. The PCFS's design was validated at RCL-32, then relocated to its present location at the ACS.

Figure 7.1-7. PCFS LCH4 Conditioning Skid

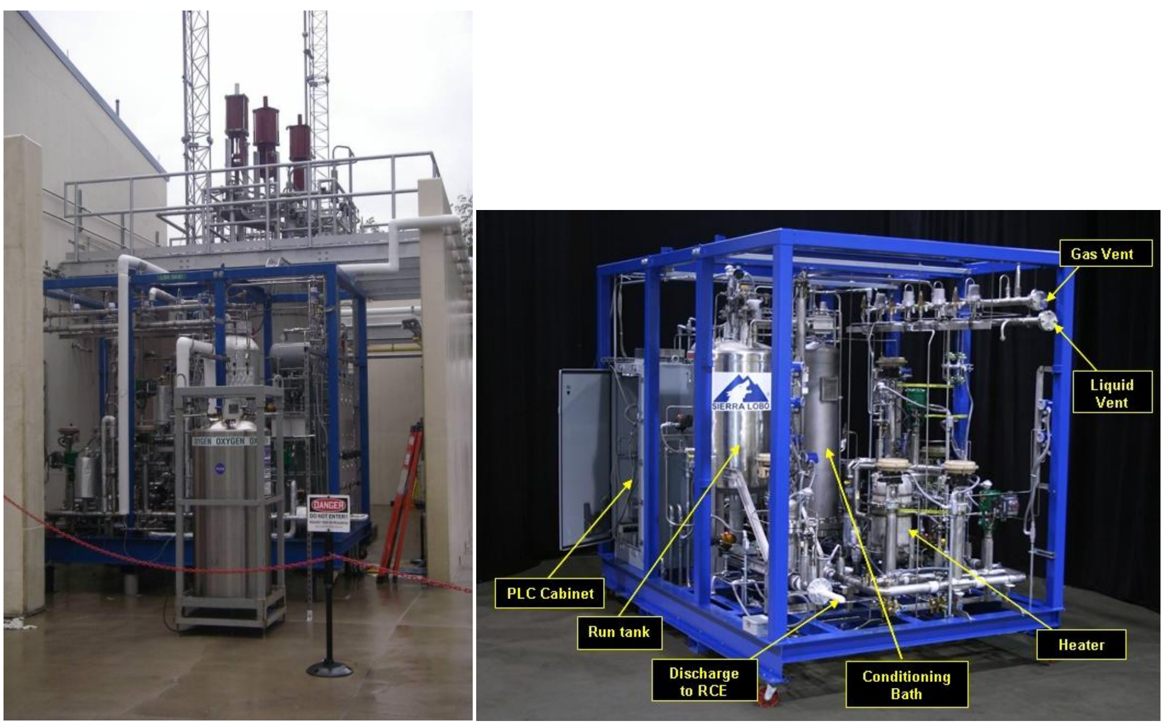

Figure 7.1-8. PCFS LO2 Conditioning Skid in Place (left) and Prior to Installation (right)

7.1.3 RCL-32

The RCL-32 and its sister cell, RCL-31, are located in Building 35-10, sharing an adjacent wall and a single-slab concrete roof (see Figure 7.1-9). They also share a control room (see Figure 7.1-10). RCL-32 and RCL-31 are sea level test stands for engines with maximum thrust ratings of 2,000 lbf and maximum chamber pressures of 1,000 psig. Table 7.1-3 summarizes the test chambers. While RCL-31 is identical to RCL-32 in design, RCL-31 is not used for engine testing at this time as the thrust stand is not installed in the cell. Installing the thrust stand (currently in storage) and adding propellant feeds would bring RCL-31 up to the same capabilities as those for RCL-32. RCL-32 was last used in 2009 for testing the PCFS. The combined RCL-31/32 facility was built in 1991.

F-1. Because they share a wall and a roof, demolishing the RCL-32 facility (defined as the complete destruction) would cause considerable collateral impacts to the adjacent RCL-31.

Integrated in Building 35-10 and adjacent to RCL-31 and RCL-32 is a room built to house laser diagnostic equipment. This room provides space for housing the equipment and pass-through openings in the wall for access to the test stands. However, the laser capability is currently not in use, nor are there any known future requirements.

F-2. The GRC laser diagnostic capability is not currently active and utilizes older laser systems not representative of the current state-of-the-art.

Figure 7.1-9. RCL-32 (left) and RCL-31 (right)

Table 7.1-3. RCL-32 Test Chamber Summary

Firing Orientation	Horizontal, axial thrust
Number of Positions	1
Maximum Thrust (lbf)	2,000
Maximum Rocket Chamber Pressure (psia)	1,000
Engine Firing Maximum Altitude	Sea level only

The current propellant capability is shown in Table 7.1-4. Other non-toxic hydrocarbon propellants can be accommodated with modifications to the test stand as required by the user.

Table 7.1-4. RCL-32 Propellants Summary

Propellant	Volume	Pressure (psi)	Flow Rate (lbm/sec)
LH2	200 gal	1,800	1
GH2	70,000 scf	2,400	3
LO2	50 gal	1,800	7
GO2	60,000 scf	2,400	4
RP-1	100 gal	1,800	3
H2O	650 gal	1,500	130 gal/min

For the past 6 years, RCL-32 has been utilized approximately 68 percent of the time. The facility was placed on standby as of June 2009 when the initial PCFS testing was completed. Typically, 3-4 people are required to operate the facility during testing. Using PCAD 100 lbf testing as a baseline, operational costs are approximately $125K/month, and $11K/month for standby.

7.1.4 RCL-32/31 Instrumentation and DACS

Strain Gauge Pressure Transducers and Load Cells

RCL-32/31 has approximately 72 dedicated strain gauge pressure transducers and load cells. The transducers range from 1 psid to 3,000 psig.

Temperature Instrumentation

RCL-32/31 has approximately 150 channels available for thermocouple measurements. RCL-32/31 has provisions for four silicon diode sensors and associated constant current excitation signal conditioning for measuring cryogenic temperatures and/or liquid level detection in tanks and vessels. RTDs are also supported by the temperature signal conditioning system. Provisions for up to 14 platinum RTDs and associated signal conditioning for measuring cryogenic temperatures are also supported by the facility.

Cameras

Three exterior cameras are located around the front of the test cells. Each camera has remote pan, tilt, and zoom functions and can be recorded on digital media. Inside the test cell is an additional ceiling-mounted color CCD camera also with pan, tilt, and zoom capabilities. There is also a provision to mount an additional fixed-position CCD camera or 35 mm camera with remote control to capture other views of the test hardware inside the cell using a portable tripod with flexible cabling.

DACS

The digital data acquisition system displays and records facility/ test specific instrumentation, and has a capacity of 128 channels of data expandable to 192 channels. The nominal scan rate is 500 Hz, but is variable and based on the channel count and conversion type. A 16-bit high-speed data acquisition system for transient data recording is available and has eight differential input channels capable of measuring signals from the millivolt level to 40 volts. Sample rates range from 100 Hz to 200 kHz per channel. A PLC is used to control the facility and research test hardware inputs and outputs, which is accomplished through a separate system from the data acquisition system. A combination of manual push buttons and graphical HMI serve as the interface for operator input and display.

Figure 7.1-10. RCL-31/32 Control Room

Other GRC Test Cells

Besides the ACS, the only other altitude stands at GRC are RCL-11 and RCL-21. RCL-11 has a maximum engine thrust capability of 50 lbf at 95 Kft simulated altitude. This stand has no sea level capability. RCL-21 is rated for 300 lbf of thrust at sea level, and 25 lbf of thrust at 95 Kft simulated altitude. So eliminating the ACS would leave a maximum of 50 lbf thrust capability for altitude testing. One other test stand, RCL-22 is rated for 2,000 lbf of thrust at sea level only. Table 7.1-5 shows the propellant capabilities for RCL-11, 21, and 22.

O-2. Closing GRC ACS will limit onsite altitude engine testing to approximately 50 lbf thrust or less.

Table 7.1-5. RCL-11, RCL-21, and RCL-22 Propellant Summary

Propellant	Volume	Pressure (psi)	Flow Rate (lbm/sec)
RCL-11			
GH2	70,000 scf	2,400	0.022
GO2	60,000 scf	2,400	0.08
Ethanol	0.5 gal	N/A	N/A
RCL-21			
LH2	25 gal	1,800	0.25
GH2	140,000 scf	2,400	0.3
LO2	5 gal	1,800	2.0
GO2	60,000 scf	2,400	1.0
HC	8 gal	1,000	N/A
Ethanol	8 gal	1,000	0.1
RCL-22			
GH2	140,000 scf	2,400	2.0
GO2	60,000 scf	2,400	4.0

7.2 JSC-WSTF Facility Description[2]

The JSC-WSTF occupies over 60,000 acres and is located along the western flank of the San Andres Mountains in southwestern New Mexico. WSTF has been a part of JSC since its construction in 1963, see Figure 7.2-1. JSC-WSTF has supported every United States (US) human space flight from Apollo through the Space Shuttle (SSP) and CxP Programs.

Although JSC-WSTF is primarily responsible for supporting NASA programs, in recent years the facility has taken on the additional mission of helping industrial firms to design, test, and operate hazardous systems on a cost reimbursable basis.

[2] A majority of information contained in this section was extracted from the JSC-WSTF website, publically available information, the August 10, 2010 site visit, and JSC-WSTF personnel interviews.

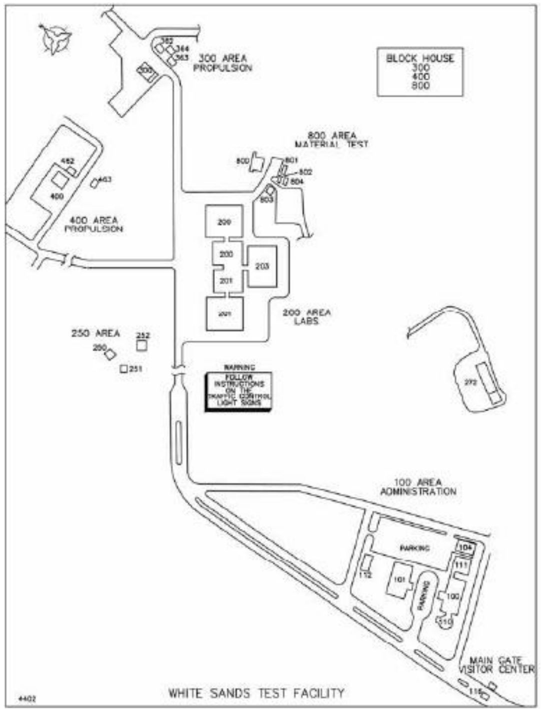

Figure 7.2-1. JSC-WSTF Office, Laboratory, and Test Area Map

7.2.1 Test Area 400

Test Area 400 is the primary area for simulated altitude engine testing using non-hazardous propellants, see Figure 7.2-2. This test area has the primary altitude test stands of TS 401, TS 403, TS 405, and TS 406. The facilities that provide the simulated altitude environment are the mechanical vacuum pump system, the SASS, and the LASS.

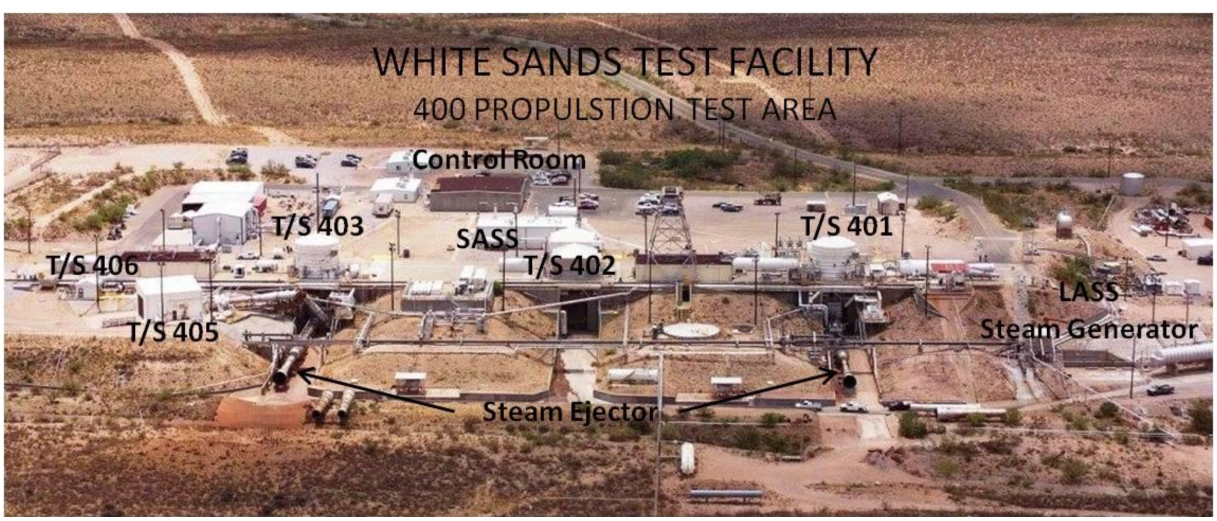

Figure 7.2-2. Test Area 400

TS 401

TS 401 is a single position altitude chamber capable of accommodating a test article (engine or vehicle) with a downward oriented thrust limited to 25,000 lbf, see Figure 7.2-3. It has three interior levels that can be reconfigured to meet test requirements. The test and propellant capabilities are summarized in Tables 7.2-1 and 7.2-2, respectively.

Table 7.2-1. TS 401 Test Capabilities

Firing Orientation	Maximum Thrust (lbf)	Test Article Conditioning (R)	Simulated Altitude, Pre-ignition/During Hot Fire (Kft)	Chamber Size (ft)	Maximum Test Article Size (ft)
Vertical Down and Horizontal	25,000	500 to 580	120/100	32 diameter x 33 high	15 x 15 x 45

Table 7.2-2. TS 401 Propellant and Pressurant Capabilities

Type	Volume (gal)	Pressure (psi)	Flow Rate (lbm/sec)*	Inlet Conditions (R)*
Ethanol	500	350		
GOX	400 scf	450 Low 3,000 High		500 to 680
Hydrazine	2,000	600		
LCH4	1,500	500	10.2	170* to 204
LH2	28,000	100		
LO2	9,500	90	16.5	163
LO2	4,200	720	16.5	163
N2O4	4,200	720		
RP/JP	500	800		
GN2		3,000		
GHe		5,500		
Air		40 to 120		

*Based on Auxiliary Propulsion System Test Bed (APSTB) heat exchanger capabilities.

TS 401 has been used for prior PCAD testing utilizing the Auxiliary Propulsion System Test Bed (APSTB) (see Section 7.2-2) and is currently configured for testing DOD Minuteman upper stage test articles. The Minuteman qualification testing concerns aging and surveillance characterization conducted on the post-boost propulsion system to examine system capabilities during storage. Proposed plans for moving ACS testing to TS 401 may require the relocation of the Minuteman testing from TS 401 to TS 403 (Appendix D). JSC-WSTF has discussed the potential for relocation of the Minuteman testing to TS 403 with the DOD. However, the Minuteman Project has expressed reluctance to reposition testing as TS 401 has established performance characteristics, and a test schedule delay could occur if TS 403 activation issues were to occur.

F-3. The Minuteman Program has not concurred with relocation of testing from JSC-WSTF TS 401 to TS 403.

The APSTB LCH4 heat exchanger is installed in TS 401. This heat exchanger was designed to obtain 170 R, but has not been fully evaluated.

Figure 7.2-3. TS 401 with Propellant Storage and Altitude Simulation Exhaust Vent System

TS 403

TS 403 (Figure 7.2-4) is a sister test stand to TS 401 with a similar configuration as described in the prior section. This test stand does not have an APSTB heat exchanger installed and is currently only posses dinitrogen tetroxide (N2O4) and monomethylhydrazine (MMH) propellant capabilities, and historically has had a low utilization rate [ref. 6].

Figure 7.2-4. TS 403 with Altitude Simulation Exhaust Vent System

TS 405 and TS 406

TS 405 is a horizontal firing stand with a 9.5 foot diameter by 28 foot long altitude chamber capable of testing both solid propellant rocket motors and hypergolic engines up to 25,000 lbf thrust, see Figures 7.2-5 and 7.2-6, and Table 7.2-3, although as currently configured the liquid propellant supply systems limits the stand to approximately 1000 lbf thrust for liquid engines. It has an altitude test capability up to 100 Kft for engine firings using the steam ejector system. Propellant capability includes N2O4, hydrazines, and solids. Liquid propellants are stored in 110-gal run tanks rated to 1,000 psia and can be saturated with helium up to 285 psi and temperature conditioned from 500 to 580 R. Currently this test stand does not have a LCH4 propellant delivery system.

Figure 7.2-5. TS 405

Figure 7.2-6. TS 405

Table 7.2-3. TS 405 Test Capabilities

Maximum Thrust (lbf)	Test Article Conditioning (R)	Engine Firing Altitude, Start/Duration (Kft)	Chamber Size (ft)	Propellant	Propellant (gallon)	Pressure (psi)
25,000*	500 to 580	250/100	28 long x 9.5 high	Solid Hydrazine Hydrazine N2O4 N2O4	NA 2,000 110 2,000 110	NA 285 1,000 285 1,000

* TS 405's liquid propellant supply system limits the stand to testing engines no larger than approximately 1,000 lbf thrust.

TS 406 is a horizontal firing altitude chamber 40-inch diameter by 8 foot long capable of testing hypergolic engines up to 1,000 lbf thrust, see Figures 7.2-7 and 7.2-8, and Table 7.2-4. The chamber has an altitude capability of 100 Kft for engine firings using the steam ejector system. Propellant capability includes N2O4 and hydrazines in 2,000-gal storage and 15-gal run tanks. Hypergolic propellants (MMH/N2O4) can be saturated with helium up to 300 psi and can be temperature conditioned from 500 to 580 R. Propellants can be pressure or pump transferred, and two propellant aspiration systems are currently installed. Like, TS 405, TS 406 does not have a LCH4 propellant delivery system.

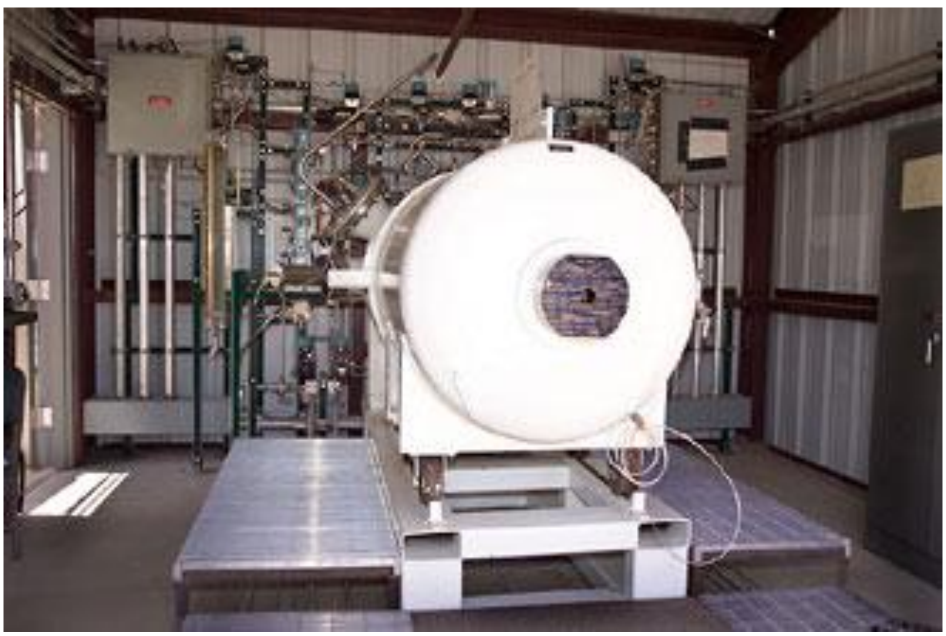

Figure 7.2-7. TS 406

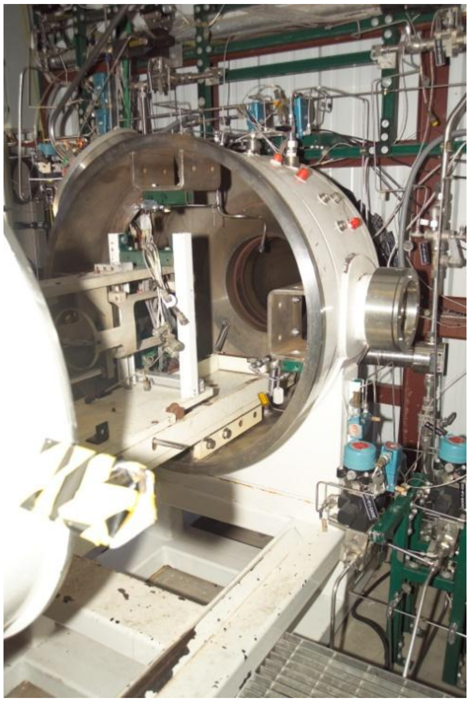

Figure 7.2-8. TS 406

Table 7.2-4. TS 406 Test Capabilities

Maximum Thrust (lbf)	Test Article Conditioning (R)	Engine Firing Altitude, Start/Duration (Kft)	Chamber Size (ft)	Propellant	Propellant (gallon)	Pressure (psi)
1,000	500 to 580	250/100	8 long x 3.5 diameter	Hydrazine Hydrazine N2O4 N2O4	2,000 15 2,000 15	300 1500 300 1500

7.2.2 Propellant Delivery Systems

The Test Area 400 propellant delivery systems are capable of providing a variety of storable and cryogenic fuels and oxidizers. The primary system of interest with respect to the PCAD testing is the APSTB and the GRC PCFS.

APSTB

The APSTB was originally designed as a LO2/LH2 test bed that can be configured in either a short or long configuration, see Figure 7.2-9. The short feedline configuration consists of 10 feet of cryogenic-line running to the engine test position. This setup was intended to simulate the propellant distribution in the Space Shuttle Orbiter. The long feedline configuration includes 225 feet of cryogenic-line and a propellant accumulator upstream of the engine test position to simulate propellant distribution along the Orbiter length.

The APSTB was reconfigured for LO2/LCH4 for PCAD testing. The system has 500 gallon LO2 and 500 gallon LCH4 tanks which can be pressurized to 415 psi. The engine inlet conditions for LO2 flow rate and temperature are 16.5 lbm/sec and 163 R, respectively. The engine inlet conditions for LCH4 flow rate and temperature are 10.2 lbm/sec and 170 to 204 R, respectively. The 170 R inlet condition requires the use of an available heat exchanger and has not been fully demonstrated in TS 401. The APSTB can supplement its 500 gallon propellant run tanks with the LO2 and LCH4 storage tanks located at TS 401 (see Tables 7.2-2 and 7.3-2).

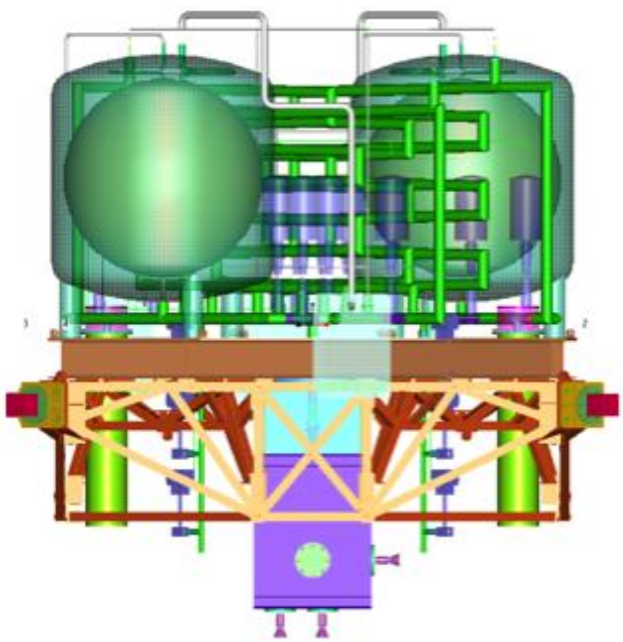

Figure 7.2-9. APSTB Graphic with Multi-Nozzle Test Article Installed

GRC PCFS Relocation

The relocation of the GRC PCFS was notionally targeted for integration into TS 401. This propellant system relocation would provide JSC-WSTF with increased versatility for LO2/LCH4 cryogenic test capability. However due to the ROM nature of the PCFS relocation estimation, JSC-WSTF personnel have limited detailed knowledge of the PCFS configuration and design requirements. A pressure system structural evaluation and analysis would be necessary before system installation and activation to meet JSC-WSTF Safety requirements. The cost and facility integration time associated with this effort was not specifically identified in the relocation and test buildup estimate for the integration of the PCFS at JSC-WSTF. Based on GRC experience, the integration and activation of the PCFS would be expected to occur over several months. This would limit LO2/LCH4 cryogenic testing in an altitude environment to TS 401 (or TS 403) using the APSTB. In addition, thermal analyses would be required to assess propellant system placement and resulting engine inlet conditions. The potential exists that current PCAD engine inlet conditions could not be achieved, even with the use of the APSTB heat exchanger installed in TS 401.

It is recognized that JSC-WSTF would ultimately locate the PCFS in a location that would meet the current and anticipated needs for LO2/LCH4 testing. Although TS 401 was originally indicated at the installation site, the PCFS may be more appropriately located adjacent to TS 403, TS 405, TS 406, or between TS 405/TS 406.

F-4. Relocation of GRC PCFS could be positioned at a variety of locations in the JSC-WSTF 400 Test Area, but would require detailed thermal and structural analyses to meet JSC-WSTF Safety requirements and engine inlet conditions prior to installation and activation.

7.2.3 Altitude Simulation

Altitude simulation in the 400 Test Area can be obtained through the use or combined use of mechanical vacuum pumps, blowers, a boiler steam generator/ejector system, and/or three chemical steam generator (CSG) modules.

SASS

The SASS consists of mechanical vacuum pumps and fuel-oil fired boilers to provide gas displacement and steam generation.

The four oil-sealed rotary mechanical vacuum pumps provide up to 20,000 standard cubic feet per minute (scfm) of air displacement. These systems can be used as a standalone system for relatively short duration or minimal impulse firings, or used in conjunction with the SASS boilers and/or LASS to precondition or maintain the test chamber pressure.

The three 800 bhp fuel-oil fired boilers power two-stage ejector sets of the altitude simulation system (Table 7.2-5). The number of boilers fired, the selection of the ejector combination, and the interchangeable diffusers allow optimization of the entire steam system to engine requirements.

Table 7.2-5. SASS Steam Generation Capability Summary

Number of Boilers	Approximate Age (yrs)	Steam Output per boiler	Duration at Thrust (hrs: lbf)
3	15	7.5 lb/s, 250 psi, and 860 R	8:1,000

LASS

The LASS is a comprehensive Test Area system which involves test chambers, vacuum pumps, vacuum valves, CSG, N2, water cooling system, LO2 feed system, alcohol feed system, and diesel pumps. However, the three CSG modules are of most interest due to their age and operational costs.

Each of the three CSG modules can be operated separately or in parallel depending on the test needs. Table 7.2-6 provides a summary of the steam generation capabilities.

Table 7.2-6. LASS CSG Capability Summary

Number of Modules	Approximate Age* (yrs)	Steam Output per CSG	Module Demand	Duration at Thrust (number of modules: min: lbf)	Module Restart/Recycle Times** (min)
3	45	180 lb/s, 300 psi, and 987 R	275 gal/min LO2 170 gal/min alcohol 900 gal/min water	1:120:4,000 2:065:7,500 3:020:15,000	5/20

* Various components have been replaced, redesigned, remanufactured, and repaired.
** Test restart driven by LO2 system (pressure, temperature, and personnel safely).

In general, the steam generator modules are approximately 45 years old. Various components have been replaced, redesigned, remanufactured, and repaired. Some components are unchanged since originally installed and because of their nature will continue to provide reliable service. The most aged and suspect aspect of the generator is the wiring. Portions and subsystems have been replaced or repaired, but a more comprehensive overhaul is required. RPT Program funds have allowed JSC-WSTF to replace a large portion of the control system, but additional funding is needed to replace the wiring. Inspection, repair, and replacement are ongoing.

Appendix B contains the following chart (Figure 7.2-10) which summarizes the PRT identified risks associated with the operation of the LASS. This chart indicates (Risks 1 and 4) a number of age and maintenance issues, which could impact LASS operations. It is recognized that the steam generator system is designed to self-safe through the actuation of a safety isolation valve (shutter valve seen in Figure 7.2-11) to minimize the potential for damage to the test article. JSC-WSTF has encountered test interruptions and delays ranging from days to weeks due to age related issues with the LASS.

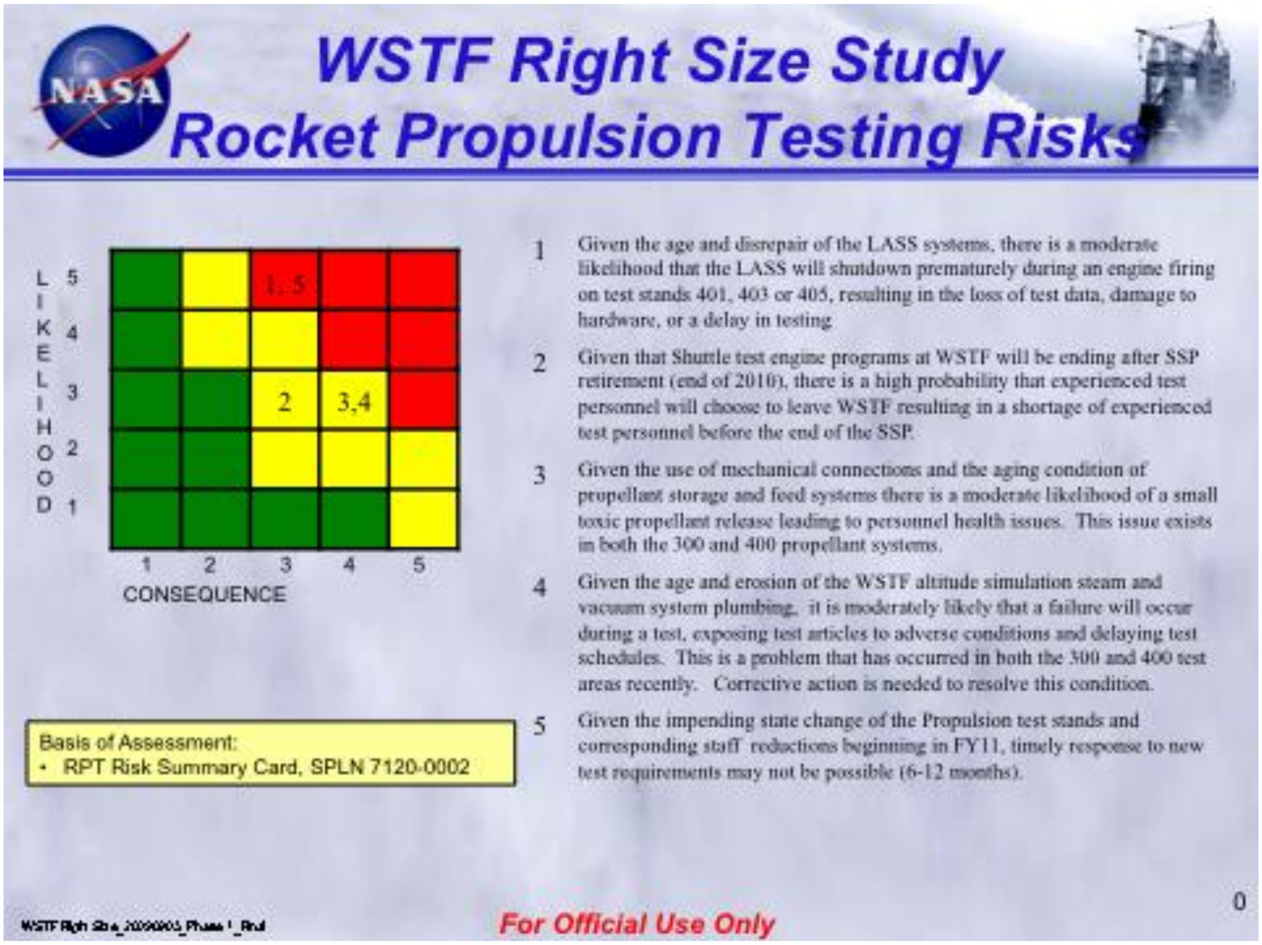

Figure 7.2-10. PRT Identified Risks for JSC-WSTF LASS Operation

Note: Items 1 and 2 appear to have their placements reversed.

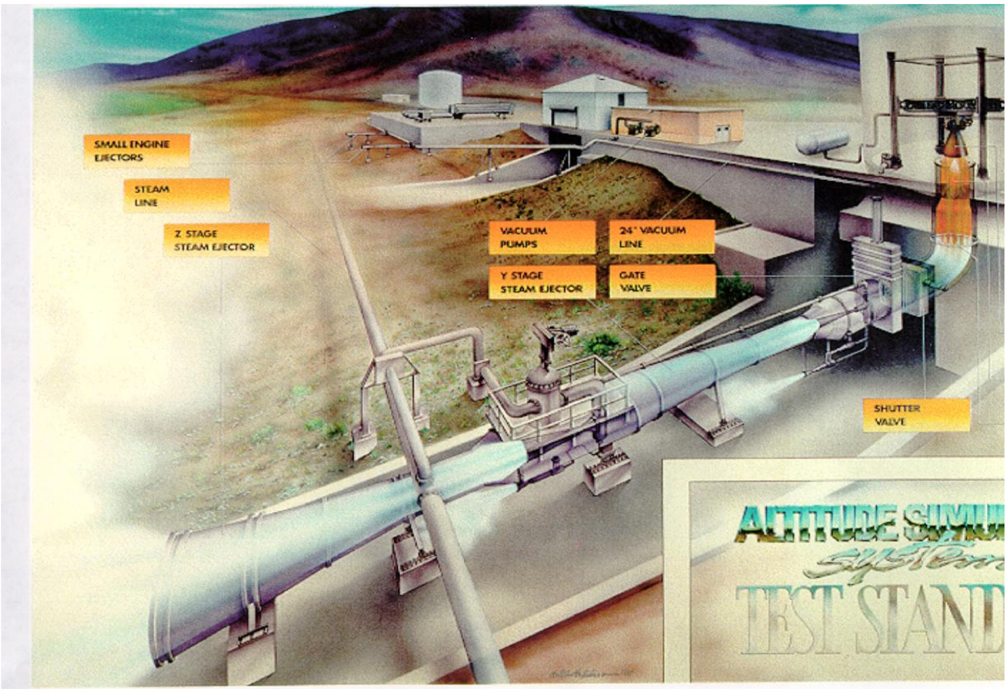

Figure 7.2-11. LASS Steam Exhaust System Components Associated with TS 401

F-5. JSC-WSTF LASS has identified reliability concerns that could impact short- and long-term test support efforts requiring this altitude simulation capability.

7.2.4 Test Area 400 Instrumentation and DACS

Current DACS

JSC-WSTF currently operates second generation DACS's consisting of Astrodata® signal conditioners and amplifiers. These systems are proven technology with sufficient spares available to assure operability. The DACS's incorporate current computing technology features for efficient and safe testing. The DACS's have the capability for 300 analog, 8 flow (frequency converters), 8 charge accelerometers and 100 digital (event) channels. Of the 300 analog channels, 180 are 7-wire circuits and 120 4-wire circuits. These circuits provide: high level transducers (0-5V); low level transducers (4-20 mA); bridge transducer; current; voltage taps; thermocouple; resistance temperature device; and strain gauge data streams.

Extensive use of both high-speed memory networks and standard network communications allows for safely automated test operations and the distribution of test results in near real-time. Graphical user interface technology provides optimum test article telemetry monitoring, and control system interaction. The DACS provides customer data processing and analysis service both in real-time for test control and monitoring at JSC-WSTF, and post-test (nominally within 24 hours) to the test requester. Currently, JSC-WSTF utilizes limited "quick look" data parameters for near real-time post test evaluation. A comprehensive data package is not certified for distribution for at least 24 hours and cannot be directly access from the test requesters' location.

O-3. JSC-WSTF DAC system does not have remote access capability for real-time data review.

Planned DACS

The JSC-WSTF Propulsion Test Office is procuring and installing the third generation of automated DACS (Figure 7.2-12). The planned baseline DACS will have the capability for 298 analog, 6 flow (frequency converters), 12 charge accelerometers , and 160 digital (event) channels. A supplemental DACS is also envisioned with approximately one-third capacity as the baseline DACS.

Figure 7.2-12. Planned Test Area 400 DACS Update
Note: Hardware procured, but funding for entire installation (baseline and supplemental) not identified.

Engine Exhaust Gas Spectral Analysis using Lasers

JSC-WSTF maintains facilities to test fire engines in altitude chambers that can be configured to support plume spectral analysis studies. JSC-WSTF has successfully supported several plume spectral analysis projects using laser analyzers. However in each case, the test requester supplied the laser equipment, and was responsible for acquiring and analyzing the spectral data.

Camera Documentation

JSC-WSTF has extensive still and video documentation capabilities. These services can be used for in situ observation and documentation, and test hardware buildup. Video documentation includes infrared, high speed, and high definition formats.

7.2.5 Test Operations and Control Room

Test operations for the 400 Test Area are centralized in the Building 400 blockhouse. The control room provides monitoring and operation of the test article, DACS, and altitude simulation systems (Figures 7.2-13 and 7.2-14). The number of test operations personnel increases with the use of the SASS and LASS. Although the reported number of personnel required to conduct an altitude test varies, it appears to range from 7 to 13. If a test requires the SASS and/or LASS, the number of personnel could approach 20 to 25.

The centralized control room allows for maximizing utilization, but limits test operations to a serial mode.

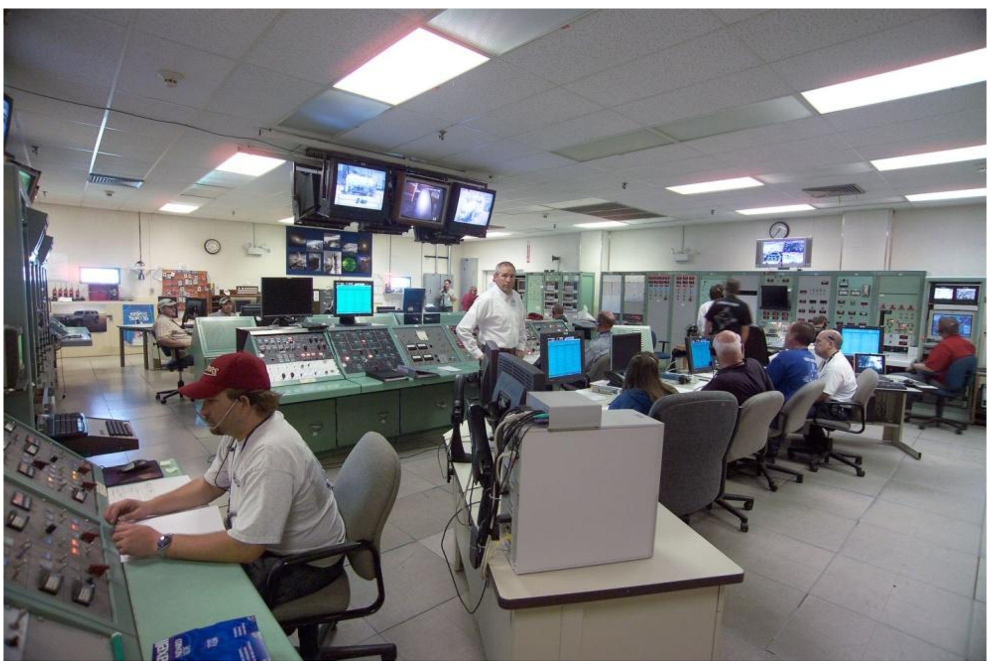

Figure 7.2-13. Test Area 400 Control Room

Figure 7.2-14. Test Area 400 Control Room

7.3 Propulsion Technology Development

While analytical tools have greatly improved in accuracy over the last 50 years and are ubiquitously applied during the development of new propulsion systems, there remains a heavy reliance on testing for demonstration of advanced concepts and for verification and qualification of flight hardware. Whether NASA's testing needed to support development of propulsion system designed for operation in vacuum or near-vacuum conditions can best be performed, from a technical perspective, in one facility requires consideration of several factors. One consideration is the planned or projected need for such testing. Others include the expected range of facility capabilities necessary to meet future testing needs, and consideration of what role test facilities play in maintaining and enhancing creativity and innovation.

It appears that at the time that the PRG recommendation to close and demolish ACS and RCL-32 was made there was an expectation that the PCAD Project would continue into FY11 and beyond. PCAD has been a primary user of both the GRC (ACS and RCL-32) and JSC-WSTF (TS 401) facilities as it has developed technology for in-space propulsion, with the eventual target being application of mature technology toward the design of the Altair lunar lander (see Appendix H). The President's proposed NASA FY11 – FY15 budget deleted PCAD, and proposed the creation of several technology projects, some of which potentially could continue the maturation of the in-space propulsion technology being developed under PCAD (see Appendix I for PCAD closeout summary). However, most of these technology activities are not included in the versions of NASA's budget being debated in Congress. Furthermore, the primary target for PCAD technology, the projected near term design initiation of the Altair vehicle, is not included in any of the various proposals for NASA's budget. As of the writing of this report, there is no explicit funding included for testing of low to midrange thrust propulsion systems (i.e., 2,000 to 25,000 lbf) operating with cryogenic propellants and requiring altitude simulated testing.

The Office of the Chief Technologist is developing technology roadmaps, one of which specifically targets in-space propulsion. However, decisions regarding NASA's technology portfolio based on these roadmaps is not expected to affect the FY11 budget. Launch vehicle providers do not appear to be interested in "green" propellant propulsion (e.g., LO2/LCH4, LO2/LH2) systems for low to midrange thrust systems. Hypergolic systems with their proven operational record and readily available mature designs are in use on operational spacecraft and baselined for commercial systems under development. This points out that without a NASA spacecraft design pull or technology project push, there will not be much need for the type of testing under consideration.

O-4. NASA facility requirements based on short- and long-term mission objectives is dynamic and likely to change. Nevertheless, the Agency has no current or future needs identified for engine testing in the 2,000 lbf range and below, which would be satisfied by the ACS, RCL-32 or TS 401.

Despite this uncertain future need, it is nevertheless worth examining the testing that can be accomplished in the facilities in question. Table 7.3-1 provides the opportunity to compare ACS, RCL32, and TS 401 in addition to three other facilities at JSC-WSTF: TS 403, TS 405, and TS 406. In terms of maximum thrust capability and test article size, TS 401 is substantially larger than ACS and RCL32. TS 405 and TS 406 most closely approximates the ACS and RCL-32 in terms of thrust capabilities and test article size. However, neither TS 405 or TS 406 currently have the infrastructure (tanks, piping, and valves) to support testing of cryogenic propellants. Only TS 401 is currently equipped for this type of testing at JSC-WSTF. Conversely all four JSC-WSTF facilities listed are equipped to test with hypergolic propellants.

Table 7.3-1. Comparison of Selected GRC and JSC-WSTF Test Facilities
Overall Facility Capability

	TS 401	**TS 403**	**TS 405**	**TS 406**	**ACS**	**RCL-32**
Firing Orientation	Dual	Dual	Horizontal	Horizontal	Horizontal	Horizontal
Maximum Thrust (lbf)	25,000	25,000	25,000**	1,000	2,000	2,000
Altitude Capability (Kft)	Ambient, 100 w/steam ejector, 220 non-firing w/vacuum pumps	Ambient, 100 w/steam ejector, 220 non-firing w/vacuum pumps	Ambient, 100 w/steam ejector, 220 non-firing w/vacuum pumps	Ambient, 100 w/steam ejector, 220 non-firing w/vacuum pumps	Ambient*, 100 GN2 blow-down nominal 130 w/diffuser pumping	Sea level
Continuous Duration at maximum thrust at 2,000	At least 105 minutes	At least 105 minutes	At least 105 minutes	N/A	3 minutes at maximum ejector flow rate	N/A

lbf						
Propellant available	LO2 GO2 N2O4 LH2 MMH LCH4 Hydrocarbon fuels(ethyl alcohol)	N2O4 MMH	N2O4 MMH Solids	N2O4 MMH	LH2 GH2 LO2 GO2 LCH4 RP-1 H2O Ethanol	LH2 GH2 LO2 GO2 RP-1 H20

* ACS has limited local ambient atmospheric pressure testing capability – can test 100 lbf thruster at ambient conditions, but highest thrust that can be tested in this configuration has not been determined.
** TS 405 is capable of testing articles generating up to 25,000 lbf, but its liquid propellant supply system limits the stand to testing engines no larger than approximately 1,000 lbf thrust.

ACS and TS 401 can both reduce test cell pressure to simulate altitudes in excess of 100 Kft. ACS uses a GN2 blowdown system, which is simple to operate, but has a relatively limited maximum run duration. This could be extended with the addition of extra GN2 tanks, but in its present configuration a typical maximum run time is on the order of 10 minutes, decreasing to about 3 minutes for the largest test articles envisioned to be tested in that facility. For component development and demonstration of new engine concepts this provides adequate continuous run duration. Rather this is more a limitation with regards to the total number of tests that could be run before the GN2 system would have to be recharged. For the 100 lbf RCE being tested for PCAD, the facility could support more than ten tests per day before requiring recharge. TS 401 has three separate systems available for reducing the test cell pressures, vacuum pumps, the SASS, and the LASS. Which system is used depends on the size of the test article, and therefore combustion products flow rate that has to be evacuated from the test cell. Continuous run times possible with the vacuum pump and the SASS are on the order of hours. With the LASS operating it is 35 minutes if all three CSGs are being used. Cost to operate the facility increase from a minimum of operating with only the vacuum pumps to a maximum for a test requiring all three CSG cans.

Consistent with the larger size of TS 401, the propellant tanks for LO2, LH2, and LCH4 are much larger at TS 401 than those available at ACS, see Table 7.3-2. For the same size engine, continuous run times possible are much longer on TS 401 than ACS. As to whether the propellant storage availability or ejector system capability will limit the maximum continuous test possible requires detailed understanding of the test article operational characteristics, but for the same size test article, TS 401 will support a much longer continuous test than ACS. Conversely, the LO2 and LH2 propellant tanks at ACS have a much higher pressure capability than those of TS 401. This is an important consideration since the general trend in propulsion system design has been increasing chamber pressure. There is no appreciable difference between ACS and TS 401with LCH4 propellant tanks pressure capability. There is also extensive storage capability for GO2 and GH2 at ACS and not at TS 401.

Table 7.3-2. Comparison of Selected GRC and JSC-WSTF Test Facilities

Available Propellants Quantity and Pressure	**TS 401**	**TS 403**	**TS 405**	**TS 406**	**APSTB****	**ACS**	**RCL-32**
LO2 Storage unconditioned, gal	13,500	13,500	N/A	N/A	500	200	50
LO2 Storage unconditioned max pressure, psi	720	720	N/A	N/A	450	1,800	1,800
LO2 Storage Conditioned, gal	N/A	N/A	N/A	N/A	500	60	N/A
LO2 Storage Conditioned max pressure, psi	N/A	N/A	N/A	N/A	450	525 psi	N/A
GO2 Storage, scf	400	400	N/A	N/A	N/A	60,000	60,000
GO2 Storage max pressure, psi	3,000	3,000	N/A	N/A	N/A	2,400	2400
LH2 Storage, gal	28,000	28,000	N/A	N/A	500	200	200
LH2 Storage max pressure, psi	100	N/A	N/A	N/A	450	1,800	1,800
GH2 Storage, scf	N/A	N/A	N/A	N/A	N/A	1,400,000	70,000
GH2 Storage max pressure, psi	N/A	N/A	N/A	N/A	N/A	2400	2400
LCH4 Storage*, gal	1,500	1,500	N/A	N/A	500	60	N/A
LCH4 Storage max pressure, psi	500	N/A	N/A	N/A	450	525	N/A
Hydrocarbon storage, gal	500	500	N/A	N/A	500	100	100
Hydrocarbon storage max pressure, psi	600 psi	N/A	N/A	N/A	450	1,800	1,800
LO2 conditioning, R	163 R	N/A	N/A	N/A	163	145 to 243	N/A
LCH4 conditioning, R	*170 to 204	N/A	N/A	N/A	*170 to 204	170 to 304	N/A

*RCL-32 LH2 storage tank was designed for use with multiple cryogenic propellants (e.g., Liquid carbon monoxide and LCH4).
** Design for use with LH2, Ethanol, or LCH4.

The GRC PCFS provides the capability to control the temperature and pressure of the LO2 and LCH4 propellant at the test article interface over a range that is not possible at TS 401. However, the PCFS can provide limited propellant flow rates, 0.16 lbm/sec and 0.5 lbm/sec for LCH4 and LO2, respectively. This effectively limits testing of methane-oxygen engines of approximately 210 lbf of thrust (Figure 7.3-1) for an ideal nozzle operating at an oxidizer-to-fuel mixture ratio (MR) of 2.9. At the PCFS optimal MR of 3.12 it would be possible to test a thruster generating another 10 to 15 lbf.

F-6. The PCFS flow rates and pressure limits support testing of thrusters generating up to approximately 210 lbf of thrust at an MR of 2.9.

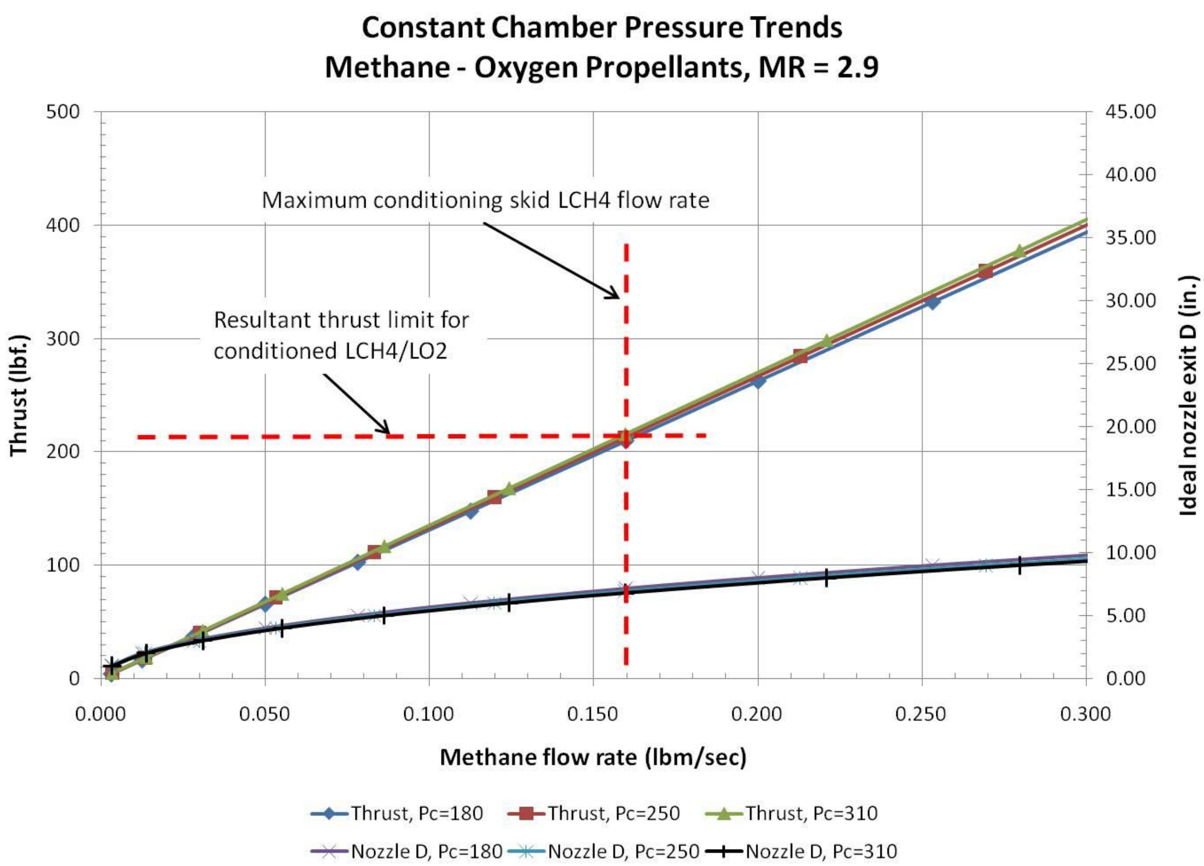

Figure 7.3-1. ACS Test Capabilities for LCH4 and LO2 Thrusters

With respect to testing LH2 – LO2 engines, ACS can supply 1.5 lbm/sec and 7.0 lbm/sec of LH2 and LO2, respectively, with conditioning capability typical of cryogenic propellant delivery system (i.e., limited capability to independently control supply pressure and temperature). Testing of LH2/LO2 thrusters is limited by supply tank pressure and by the stand maximum thrust capability. The LH2 and LO2 supply tanks are limited to 1800 psi, therefore the highest chamber pressure achievable for a pressure thruster is in the 1,000 to 1,100 psi range, the exact value dependant on the injector detail design. The flow rate does not limit the maximum achievable thrust, as a LH2 flow rate of 1.5 lbm/sec will support an ideal thruster that generates approximately 4,800 lbf of thrust at a chamber pressure of 1,000 psi and an MR of 6.0 (see Figure 7.3-2). Also note that TS 401 is limited to 100 psi supply pressure for LH2 (Table 7.2-2). This low pressure is of limited value for testing pressure fed thrusters, since it limits the achievable chamber pressure in the test article to approximately 55 to 60 psi.

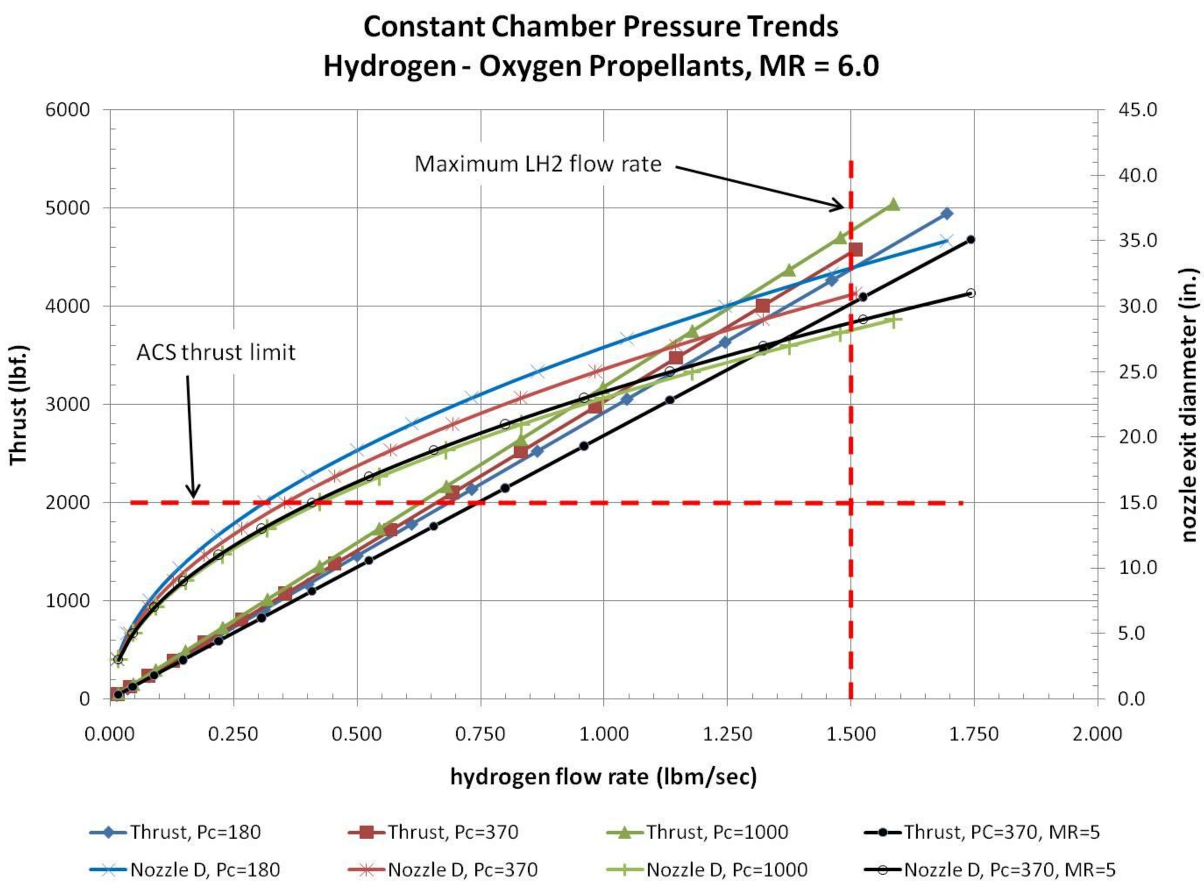

Figure 7.3-2. ACS Test Capabilities for LH2 and LO2Thrusters

As a generalization, the JSC-WSTF Test Area 400 facilities are appropriate for simulated altitude system-level testing and qualification of flight hardware, while the GRC RCL is optimized for lower-technology readiness level (TRL) research and development. The infrastructure and configuration management at JSC-WSTF is directed more to the requirement-satisfaction environment, while GRC supports an iterative and repetitive component testing approach used in development. In addition, the ACS has a maximum run time for continuous altitude testing of approximately 10 minutes, depending on engine size and configuration. Qualification and certification test for in-space propulsion typically require continuous operation for much longer time frames, such as those possible at JSC-WSTF.

Therefore, while it is possible to conduct system level qualification/certification testing in ACS, because of its small test cell size, low thrust capability, short run time, and small test crew (all relative to TS 401), it is more suited than TS 401 for component and subsystem development testing (where the thrust does not exceed ACS capability). Conversely, while it is possible, and has been done, to conduct low thrust component or subsystem tests in TS 401, because of its large test cell size, high thrust capability, extended continuous run time, and more complex facility systems as evidenced by the larger test crew size (all relative to ACS), it is more suited than ACS for system level development and qualification/certification testing.

O-5. TS 401 is more suited than ACS to long-duration continuous test runs typical of system-level and qualification/certification testing.

O-6. The ACS is more suited than TS 401 to low thrust, component-level development testing not requiring hypergolic propellants.

Availability of facilities outside NASA with similar capability, which the Agency and its propulsion contractors could use to augment (i.e., increased testing need) or replace (i.e., unavailability of NASA facility due to testing mishap) internal NASA capability, is a consideration in determining what facilities NASA should retain. Therefore it is appropriate to consider how unique the capabilities available in ACS and TS 401 are to other domestic test facilities. A summary of the facilities closely approximating the capabilities available in ACS, RCL-32, and TS 401 is provided in Appendix J. The table shows data extracted from the Chemical Propulsion Information Analysis Center (CPIAC) test facilities database for altitude propulsion test facilities having a thrust capability from 100 to 100,000 lbf. There are 12 facilities in the thrust range of 100 to 10,500 lbf listed as being active, and another listed as inactive, but in good condition. However, none possess the three cryogenic propellants (LO2, LH2, and LCH4) available at ACS, nor the high pressure capability in both LO2 and LH2. Capability to test hypergolic propulsion systems in this thrust range is readily available. There are five active facilities listed in the thrust range from 20,000 to 100,000 lbf, plus a sixth mothballed, but listed as in excellent condition. However, none have the three cryogenic propellants currently available at TS 401. There is a high supply pressure for LO2 and LH2 at Aerojet's Azone A-8, but the facility can only simulate up to 30 Kft altitude. Three of the five active facilities in this thrust range have the capability to test hypergolic propellants.

While this does not represent an exhaustive investigation into non-NASA facilities, it does appear that the cryogenic propellant capabilities available at ACS and TS 401 are not readily available outside of NASA. Furthermore, the ACS LO2 and LH2 propellant run tank pressure capability appears to be unique nationally for facilities able to simulate 100 Kft and higher altitude

F-7. LH2, LO2, and LCH4 availability and utilization at ACS and TS 401 is a unique national capability for altitude test facilities.

F-8. The high pressure (1,800 psi) LH2 and LO2 availability at ACS is a unique national capability for altitude test facilities capable of simulating greater than 30 Kft altitude.

Although this report is intended to be an objective, technical assessment of the facilities and test stand capabilities, the NESC team believes there are certain intangible aspects that should at least be considered in the cost, schedule, and technical equation by the decision makers. One consideration when assessing the value of experimental facilities is the effect it may have on Agency creativity and innovation. Technological advancement is a self-perpetuating process whereby each new concept or idea leads to another, the rate of knowledge creation increasing with increased exposure to new ideas. While some concepts or ideas for improving space transportation propulsion can be proved or disproved analytically, most require some level of experimental demonstration. Experimental evaluation of new ideas readily is valuable to innovation and creativity because it enhances the process of creating new knowledge in two ways. First, experimental capability often leads to good ideas being implemented. Secondly, it allows ideas to be continually proposed supported by comparison to sophisticated analytical models. In either case, knowledge creation can be enhanced by modern test capability.

Ideally a talented pool of scientists, engineers, and technicians should have ready access to laboratories and test cells to exercise their ideas. To be most useful, the experimental area should operate as informally and as autonomously as possible, consistent with personnel safety and facility value considerations. Additionally, the facility should operate as efficiently as possible to preclude ideas from being discarded primarily because they are too expensive to demonstrate. These two considerations, informality and minimal cost of operations, favor specialized facilities optimized to do a certain kind of testing. Conversely, a facility designed to do development and qualification testing of an integrated system will tend to be larger, have more energy on-site, have greater flexibility in the range of conditions it can simulate, and be more difficult to automate. Therefore, it will tend toward greater formality and cost in its operation. In the context of this assessment, ACS tends to be described by the former and TS 401 more towards the latter. TS 401 can, with some investment, be configured to meet all the test requirements provided by ACS.

The vacuum pumps available in TS 401 are typically used for lowering the pressure in the test chamber prior to start of the hotfire test. In TS 406 vacuum pumps have been used to maintain vacuum conditions when operating hypergolic vernier thrusters. Generally vernier thrusters produce less than 50 lbf of thrust. At TS 401, it may be possible to test small thrusters and igniters (short duration tests) and still maintain altitude conditions with only the use of the vacuum pumps, which can withdraw 20,000 scfm from the test cell. In this configuration the number of personnel required to run a test at TS 401 is of the same order as required to run a similar test at ACS. However, presumably operation of a methane or hydrogen thruster for any appreciable test duration would not be supported with the vacuum pumps alone and would require the use of the SASS as a minimum. For example, a 40 lbf LCH4-LO2 thruster operating at a chamber pressure of 180 psi will generate 34,520 cubic feet per minute of hot gas at approximately 1780 R. Such a volumetric flow rate, in lieu of a gas cooling system to cool and condense the gases, could not be accommodated by the vacuum pump alone and maintain vacuum conditions. Per communication with JSC-WSTF personnel, SASS can accommodate testing of LCH4-LO2 or LH2-LO2 generating approximately 1,400 lbf thrust. Thrusters generating 1,900 lbf or more of thrust will require operation of the LASS. The exact transition from SASS to LASS requires more detail definition of the thruster, and further analysis of the ejector and exhaust system at TS 401. Therefore to test in TS 401 over the range that can be tested at ACS the number of personnel required at TS 401 will be more than at ACS (on the order of 20 for TS 401 versus 5 for ACS) because of the extra personnel needed to operate SASS or LASS. Assuming this represents a mix of engineers, scientists, and technicians, this would represent an additional cost on the order of $100K for a month long test series. There are other costs associated with conducting a test (e.g., consumables, maintenance and repair overhead, etc.), but none of these trend towards reducing this cost difference. Therefore, if TS 401 is the only internal Agency facility available to perform midrange propulsion altitude testing of any type in the Agency (i.e., closure of ACS), it may have a detrimental impact on the pursuit of new and innovative cryogenic propulsion concepts.

The discussion in the preceding paragraphs assumes that there is active support for the scientists and engineers to develop their ideas and invest in the cost of doing the required testing. This support can come from a variety of sources, ranging from formal projects and programs created specifically to address technology or capability gaps to less formal sources such as Center Director Discretionary funded activities, NESC technical assessments, Technology Innovation Partnerships Program (TIPPs), and others. Over the last 20 years the Agency has been unable to provide consistent support for the development of ideas that would best be validated in the ACS, and with the impending end of the SSP, the only identifiable customer for the TS 401 is the DOD Minuteman testing. Consideration of a facility's, in this case ACS and TS 401, impact on the creativity and innovation at a given Center or across the Agency is academic if there is no plan to fund the development of relevant new concepts and ideas that need those facilities for demonstration.

7.4 Safety

Safety considerations in the process of deciding whether to move the ACS and RCL-32 testing and PCFS from GRC to JSC-WSTF are concerned with system safety. Both locations have capable safety organizations and can be expected to perform appropriate safety reviews prior to performing tests, and therefore the only particular concerns to be evaluated are system chemical and materials compatibility and the need for adequate quantity-distance (QD) from an explosives safety standpoint.

The QD analysis that was performed to justify the siting of the system at GRC was reviewed, see Reference 7 and Appendix K. No significant concerns were identified. Similarly, the QD values obtained from that analysis were overlaid on the JSC-WSTF site plan, and the distances between facilities were found to be adequate [ref. 8].

Therefore, from a QD safety standpoint, there are no significant distinguishing issues between the GRC ACS/RCL-32 and the JSC-WSTF 400 Test Area.

F-9. GRC or JSC-WSTF are both adequate, from a safety aspect, for placement and operation of altitude testing of low to midrange thrust cryogenic engines.

7.5 Cost and Resources

7.5.1 Methodology

IPAO led the cost assessment at the request of NESC for this report. Their report was partnered with NESC and included in Appendix L. The cost and schedule assessment was based on a review of pertinent technical and programmatic documents along with interviews with appropriate key personnel from GRC and JSC-WSTF. The documents reviewed included the SOMD PPBE PRG, historical cost data, facility studies, technical documents, and previous assessments. The interviews were conducted with technical experts, study leads, project management personnel, and cost estimators. This effort was performed in support of the NESC technical team. The technical team's programmatic' experiences and opinions contributed to the cost and schedule assessment.

The PRG Decision Package recommendation does not include all the costs the Agency will incur for demolishing the GRC ACS and RCL-32, and relocating the PCAD testing to JSC-WSTF. Nonrecurring costs for demolition (ROM estimate of $3 to $5M) are not included in the PRG. Only the non-recurring ROM cost estimate for dismantling, relocation, and installation of approximately $800K is identified. The demolition resources would have to come from the Agency Strategic Institutional Investment Funds. Potential nonrecurring cost risks for capital upgrades for the DACS (if the DOD Minuteman testing is moved from TS 401), heat exchanger, or pre-test build up costs that the Agency might incur were are not presented or discussed. The PRG only includes the recurring operations and maintenance cost estimates for the ACS and RCL-32 reflecting the potential cost avoidance if demolished. However, the potential recurring cost risks for capital upgrades, higher testing charges, maintenance costs (if the Minuteman testing is moved from TS 401), and travel of research personnel to support testing that the Agency may incur due to the relocation are not included or discussed. The recurring cost risks could be $350K per year or more depending on the amount of testing moved to JSC-WSTF. Those costs are related to, but not limited to, GRC researcher personnel temporary relocation; differences in testing costs between GRC and WSTF; and additional maintenance costs for TS 401 if Minuteman testing is moved to TS 403. A summary of the identified cumulative non-recurring and recurring costs are shown in the Figure 7.5-1. The bar chart is the potential cost of demolishing ACS/RCL-32, and moving the PCAD testing from GRC to the JSC-WSTF. The black line is the combined operations and maintenance (O&M) cost for those facilities through FY15. Table 7.5-1 is a tabulation of the potential cost risks associated with facility demolition, and transfer of work from GRC to JSC-WSTF.

F-10. The SOMD PPBE FY12 PRG Decision Package recommendation does not include all the costs the Agency will incur for demolishing the ACS and RCL-32 at GRC, and moving testing and functions to JSC-WSTF.

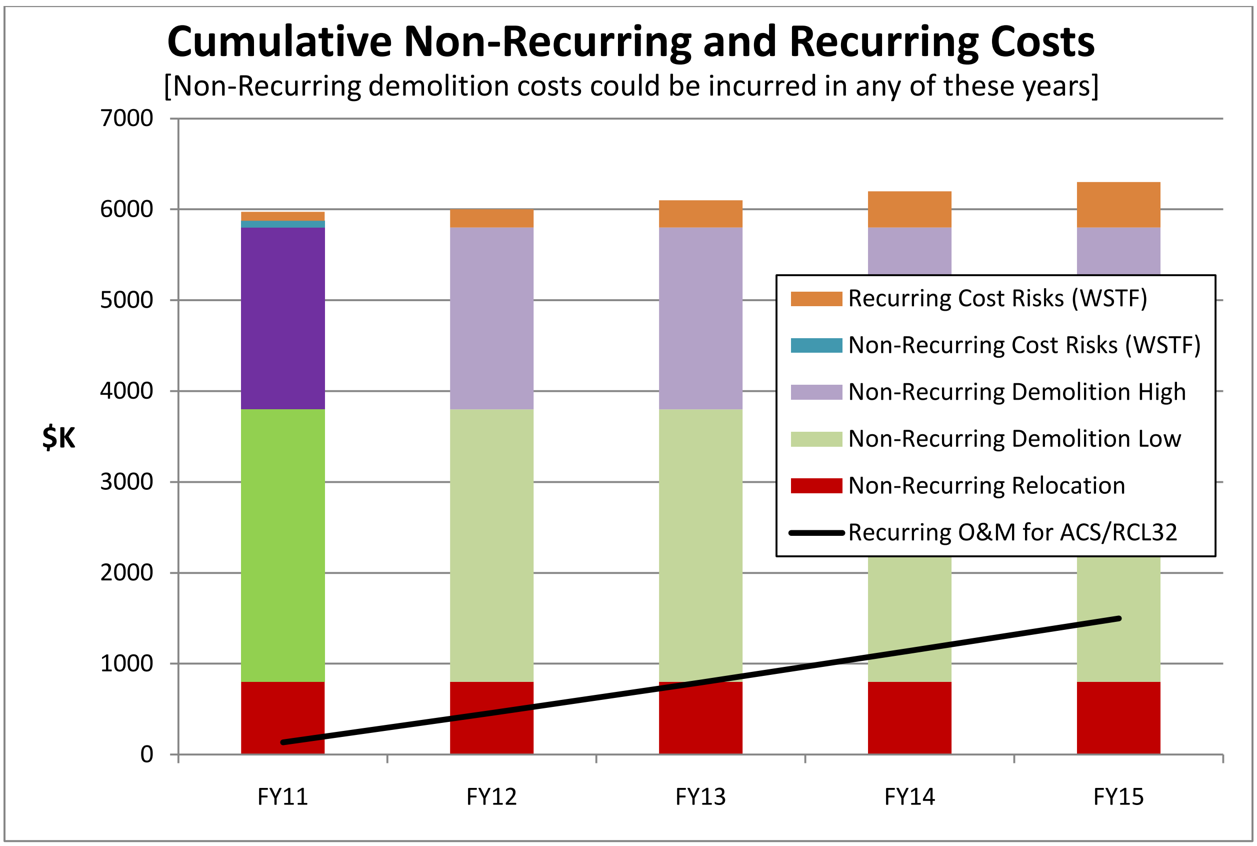

Figure 7.5-1. Summary of the Cumulative Non-Recurring and Recurring Costs

The cost information provided are primarily ROM estimates with the basis being engineering judgment based on past experiences involving similar activities. Most of the basis for estimate is not well documented or supported by data. Only several of the cost estimates are supported by actual historical cost data, those incurred by PCAD for testing at both facilities.

F-11. The costs provided to the NESC are primarily ROM estimates with the basis being engineering judgment based on past experiences involving similar activities.

The ACS is a relatively new facility and began operating in November 2009. The suggested demolition of a new facility is intuitively difficult to accept without a considerable cost payback. In an attempt to find a measure to compare the utility "newness" this team settled on an Agency-accepted facility measure called deferred maintenance (DM). DM is the total of essential, but unfunded, facility maintenance work necessary to bring facilities and collateral equipment to the required acceptable facilities maintenance standards. It is the total work that should be accomplished, but that cannot be achieved within available resources. It does not include new construction, additions, or modifications. Nor does it include any of the ancillary utilities or facilities (e.g., tank farm, test equipment, etc.). DM does include unfunded maintenance requirements, repair, replacement of obsolete items, and Construction of Facilities (CoF) repair projects. The FY09 DM assessment for ACS (B147) is $0. The DM assessment for TS 401 (B401) is $847K and TS 403 (B403) is $1,149K. The GRC RCL is listed as one group of test cells (B35) with a DM assessment of $2,781K. Although DM for RCL-32 or RCL-31could not be determined individually, it should be noted that they are the newest of the RCL test cells (built in approximately 1991)

O-7. The NASA FY09 DM assessments indicate the costs are higher for the JSC-WSTF (Bldg 401) at $846,699 compared with the ACS (Bldg 147) at $0. The DM costs for RCL-32 could not be cleanly extracted.

The demolition of ACS and RCL-32 together has a ROM estimate of $3 to $5M. However, the estimated maintenance cost of the facilities is approximately $312K per year ($180K for ACS; $132K for RCL-32). The cost of maintenance appears to be relatively low compared to the cost of demolition.

Table 7.5-1. Recurring/Non-Recurring Cost Risks

Non-Recurring Cost	PRG Recommendation	Additional Costs	Cost Risks	Assessment Comments
Demolition	No cost included	$3-5M		Cost of demolition was not included in PRG. The GRC CoF ROM estimate to demolish both ACS and RCL32 is $3-5M. This would have to be from the Agency Strategic Institutional Investment Finds.
Capital Upgrade -PCFS Installation	$800K			Based on JSC-WSTF ROM estimate to dismantle ($100K) relocate ($20K) and to install ($650K) Skid and other items from ACS and RCL-32

-DACS -Heat Exchanger -New Propellant Conditioning System			75K Unknown -$1.0M Design -$1.8M Build -$3.0M Install	JSC-WSTF ROM if AF MM moves from TS 401 Unknown requirement Based on New Propellant Conditioning System ROM Estimate by GRC

Recurring Cost	**PRG Recommendation**	**Cost Risks**	**Assessment Comments**
R&T personnel relocated to support testing	No cost included	~$50-150K/Year	Cost of R&T to support testing was not included in PRG. If R&T personnel remained at GRC but traveled to JSC-WSTF for testing these costs would be incurred. Varies by duration and number of personnel
Testing	No cost included	>~$200K/Month (Estimate Delta)	Based on historical charges to PCAD testing at JSC-WSTF may be higher than GRC; $146K/Month ACS, $125/Month RCL32, ~$350K/Month (based on PCAD historical at JSC-WSTF), Ranged from $300-$380K including a 100 lbf LO2/LCH4 Integrated RCE Test. Tests may not be fully comparable as the engine thrust differed between ACS and TS 401. A detailed estimate for the same exact test required for true comparison.
Sustainment	$768K through FY15 for ACS $729 through FY15 for RCL32		PRG includes GRC O&M costs escalated from ACS $15K/Month RCL32 $11K/Month
Sparing/maintenance		Unknown magnitude of maintenance or sparing cost	The age difference of the facilities has not been taken into consideration. Age and disrepair of LASS systems, along with

		differences $100K/Year maintenance increase if MM moves to from TS 401	altitude simulation steam and vacuum system plumbing at JSC-WSTF were cited as risks with relatively high likelihood in the "Right Size Study". The ACS is only two years old.

8.0 Overall Considerations

The subject of consolidating and/or relocating propulsion testing capabilities has been studied many times in the recent past. There are multiple presentations and reports on the subject (Appendices A, B, C, D, and G). It is important to note that the NESC team had difficulty in comparing the ROM cost estimates associated with this assessment. There were often different and sometimes conflicting estimates. The cost estimates provided were considered the best values that could be obtained given the fidelity of the JSC-WSTF "Right Sizing" effort. Although due diligence was exercised in obtaining correct data, there was not sufficient resources and time to penetrate in great detail on specifics. Another important point is that the uncertainty in the direction for the Agency was made it difficult to assess the propulsion needs and therefore the future testing requirements.

In general, the NESC team finds that there are unique capabilities available at ACS and RCL-32 that are not available at TS 401. These include GO2/GH2 capability and higher LO2/LH2 propellant pressures. These capabilities coupled with the LCH4 capability provide a unique redundancy between ACS/RCL-32 and TS 401. Additionally, ACS appears to be a unique national capability with its LO2/LH2 pressures at altitude.

History indicates that these facilities (i.e., ACS, RCL-32, and TS 401) have not been heavily utilized, certainly below their capacity [ref. 6]. In addition, with the uncertainty of the Agency's direction, there does not appear to be defined propulsion testing requirements or needs for the future. This is especially true of propulsion testing at the 2,000 lbf range and below. However, that is not to say that future Agency needs will not change or become better defined. Any future needs should be carefully understood and vetted before making significant changes to any of the propulsion stands, especially in the case of irreversible changes like facility demolition.

O-8. Rocket test facilities (including RCL-32, ACS and JSC-WSTF 401) have historically had a low utilization rate.

Although there are no current plans to use ACS or RCL-32, the loss of those facilities will have an impact on GRC researchers and needs to be considered by the Agency. At a minimum, any research work moved to JSC-WSTF will add costs and inconvenience to GRC researchers.

Collaboration between the researcher, test engineers, and technicians will become more important with resources spilt across two Centers. The NESC team does not see these as insurmountable issues, but aspects for which decision makers need to be cognizant.

The reclama paper written by GRC (Appendix F) formed the basis for many of the items assessed and the following summary addresses those concerns. First, from a technical capabilities perspective, there is no technical reason why 2,000 lbf altitude and sea-level cryogenic propellant testing cannot be conducted at JSC-WSTF rather than GRC's ACS or RCL-32. Turn-around and throughput times based on discussions of previous PCAD testing at JSC-WSTF indicate the times are roughly comparable to GRC. This is notional and not based on objective data as the prior testing at these two facilities have been with two different thrust engines. There is little information available to make a true comparison because there have not been equivalent tests conducted at both sites. If RCL-32 is closed, then this would eliminate current 2,000 lbf thrust sea-level testing capability. JSC-WSTF has flexible capability, but nothing in that range immediately available. TS 401 or TS 403 may be capable of sea-level testing, but specific analysis would have to be done to assure no damage to these altitude facilities.

Additionally, the "WSTF Right Size" Phase 1 assessment (Appendix B) noted there is moderate risk associated with the LASS system at JSC-WSTF. The age-related degradation of the LASS systems provides moderate likelihood that the systems will shut down during an engine firing and result in loss of data, delays in testing, and/or hardware damage.

Experimental measurements are a concern in the GRC Issues Paper. GRC does have a more current DACS. JSC-WSTF has an analog system, which has satisfied current and prior customers (including PCAD). Integrated in the RCL Building 35-10 and adjacent to RCL-31 and RCL-32 is a room to house laser diagnostic equipment. This room provides space for the equipment and pass-through openings in the wall for access to the test stands. However, the laser capability is currently not in use, nor are there any plans to use it. Additionally, the lasers are older technology and may be of limited value. JSC-WSTF has accommodated user-supplied laser analysis equipment in the past.

The NESC team's opinion is that both facilities are meeting customer needs with respect to data acquisition and reporting.

An area of interest raised by GRC is the utility of the PCFS currently installed into the ACS. The skids appear to be only capable of supporting engines with 225 lbf thrust or less. JSC-WSTF will need to fully understand the design and capability of the PCFS to determine its applicability in Test Area 400. TS 401 with the installed heat exchanger and the use of APSTB has greater thrust range due its larger flow rate capability. The current heat exchanger has not been tested to the same temperature range that the PCFS provides. If JSC-WSTF is able to provide the necessary inlet conditions with their current equipment (i.e., APSTB) then the PCFS could provide additional capability if the Agency decides to relocate them. Again, engine and component interface analysis will be required to determine the utility of the PCFS. This NESC team noted a disparity in costs associated with integrating the PCFS into TS 401. It should be noted that if the PCFS is moved to JSC-WSTF, there will be a time period before this system has been relocated and operational. For that time period there may be no Agency cryogenic LCH4 testing capability of the parameters required by PCAD. APSTB may be able to bridge that gap depending on engine requirements.

Another area of concern is the impact to GRC to demolish ACS and RCL-32. As it stands, the PPB&E PRG for 2012 recommends demolishing both facilities. The costs of demolishing are not accounted for in the PRG and could be significant. There are numerous supporting systems and utilities such as GN2, gaseous helium, power, water, and communication lines that are interconnected with ACS, RCL, and other GRC facilities. In addition, RCL-32 shares common structure with its sister cell RCL-31. Both share a common ceiling and a blast wall separating the two cells (along with utilities, etc.). Demolition would require significant planning and may not be practical for continued RCL-31 operation.

Generally, the control rooms at both sites appear to be capable of meeting testing needs. JSC-WSTF has one control center for four separate test stands. GRC has a control room dedicated to ACS and another one dedicated to RCL-31/32. The likelihood of tests competing for control room space is greater at JSC-WSTF.

There are some general items of interest gathered from reading the large number of presentations and reports mentioned earlier. For example, Appendix D noted that the most significant impact to moving work is "*not from the transfer of the O&M of the facilities but from the consolidation of testing and activities to be performed in the facilities*". There is no projected testing for any of these facilities after 2010 and the Minuteman testing through CY14. Part of the assumptions for moving the PCAD testing from ACS to the cryogen-capable TS 401 is that Minuteman would be moved to TS 403. It was not clear that the Minuteman Project concurs with this relocation. Appendix D indicates that JSC-WSTF is currently testing in the Technology Readiness Level (TRL) 4-5+ range, but lower TRL tests have been performed. Test stand capability does not preclude lower TRL testing.

Finally, in reviewing the costs associated at either Center with the proposed PPB&E guidance, it was difficult to get direct comparisons to contrast the actual costs. Therefore, the NESC team can only identify where cost risks may lie. First, cost of demolition will be considerable and needs to be weighed against the cost of maintaining the facilities until Agency direction and cryogenic propulsion testing needs are better identified. There are additional maintenance costs associated with moving Minuteman testing from TS 401 to TS 403. There is an estimated $75K one-time DACS upgrade cost to move Minuteman to TS 403. In addition, Minuteman pays $100K annually for maintenance to TS 401. These costs will have to be accounted for if Minuteman is relocated. The NESC team originally intended to review and comment on costs associated with maintenance and testing between the two sites. Acquiring comparable costs was difficult. The team considered comparing O&M costs for the test stands at both sites. After reviewing the data in the Agency's Real Property Inventory Database and then understanding that differences occur in what is reported in those numbers by Center, it was decided not to draw any conclusions relative to O&M costs. If O&M costs are a significant delineator in the decisions process, then the NESC would suggest that Agency experts assess this in greater detail. Likewise, it was difficult to get direct comparison costs for testing. PCAD did test at both sites. At GRC the testing costs were $146K/month for ACS and $125K/month for RCL-32. The historical cost of PCAD tests at JSC-WSTF are approximately $350K/month. As has been identified, the nature and fidelity of the tests at the two sites may not have been similar (e.g., thrust level, test duration, etc.). More analysis would be required to draw any definitive cost conclusions.

The cost of relocating the PCFS is difficult to assess until JSC-WSTF fully understands the design and capabilities of the skids. A ROM cost of $800K was used by the JSC-WSTF "Right Size" assessments to disassemble, transport, and install the system at TS 401. The JSC-WSTF basis for that estimate was not available to this team. GRC documentation shows the cost of installation at ACS was $3M. The disparity needs to be further assessed. Finally, travel costs associated with GRC researcher travel have been estimated at $120K per year. This is based on 5 months estimated travel and may not reflect actual costs.

Another important intangible is the age of the ACS facility. ACS is a relatively new facility and only begun operating in November 2009. Inherently, the age of the facility should be a positive attribute. Determining fair comparison of facilities is difficult. The NESC team looked at the DM values for the different facilities. It should be noted that the ACS DM is currently at $0. RCL-32 is not readily discernable from the data for the entire complex of RCL test stands ($2.7M). The DM estimate for TS 401 is currently at $847K, while TS 403 is at $1.1M.

In the course of researching documentation and attempting to understand RPT Program authority, the NESC team debated over the clarity and possible confusion within a particular paragraph of NPD 8081.1 NASA Chemical Rocket Propulsion Testing. The following excerpt from Section 2 (Applicability), subsection b reads:

> "*This NPD applies to all NASA programs, projects, and chemical rocket test facilities utilized for certification, developmental or acceptance testing and for engines of 1000 pounds of thrust and greater and all test activities performed in those facilities, regardless of thrust level.*"

The statement is confusing in its interpretation. It appears to provide limited applicability (greater than 1,000 lbs of thrust), but then applies to all testing activities regardless of thrust level (assumed to mean planning and approval).

O-9. NPD 8081.1 Section 2, paragraph b., second sentence: appears to provide limited applicability (greater than 1,000 lbs of thrust), but then applies to all testing activities regardless of thrust level (assumed to mean planning and approval).

9.0 Findings, Observations, and NESC Recommendations

9.1 Findings

The following findings were identified:

F-1. Because RCL-32 and RCL-31 share a common wall and roof, demolishing the RCL-32 facility (defined as the complete destruction) would cause considerable collateral impacts to the adjacent RCL-31 facility. (page 26)

F-2. GRC laser diagnostic capability is not currently active and utilizes older generation laser systems. (page 26)

F-3. The DOD Minuteman Program has not concurred with relocation of testing from JSC-WSTF TS 401 to TS 403. (page 32)

F-4. Relocation of GRC PCFS could be positioned at a variety of locations in the JSC-WSTF 400 Test Area, but would require detailed thermal and structural analyses to meet JSC-WSTF Safety requirements and engine inlet conditions prior to installation and activation. (page 38)

F-5. JSC-WSTF LASS has identified reliability concerns that could impact short- and long-term test support efforts requiring this altitude simulation capability. (page 41)

F-6. The PCFS flow rates and pressure limits support testing of thrusters generating up to approximately 210 lbf of thrust at an MR of 2.9. (page 48)

F-7. LH2, LO2, and LCH4 availability and utilization at ACS and TS 401 is a unique national capability for altitude test facilities. (page 51)

F-8. The high pressure (1,800 psi) LH2 and LO2 availability at ACS is a unique national capability for altitude test facilities capable of simulating greater than 30 Kft altitude. (page 51)

F-9. GRC or JSC-WSTF are both adequate, from a safety aspect, for placement and operation of altitude testing of low to midrange thrust cryogenic engines. (page 53)

F-10. The SOMD PPBE FY12 PRG Decision Package recommendation does not include all the costs the Agency will incur for demolishing the ACS and RCL-32 at GRC, and moving testing and functions to JSC-WSTF. (page 54)

F-11. The costs provided to the NESC are primarily ROM estimates with the basis being engineering judgment based on past experiences involving similar activities. (page 54)

9.2 Observations

The following observations were identified:

O-1. The demolition of the ACS facility and infrastructure would incur collateral impacts to other GRC operations. (page 21)

O-2. Closing GRC ACS will limit onsite altitude engine testing to approximately 50 lbf thrust or less. (page 29)

O-3. JSC-WSTF DACS does not have remote access capability for real-time data review. (page 42)

O-4. NASA facility requirements based on short- and long-term mission objectives is dynamic and likely to change. Nevertheless, the Agency has no current or future needs identified for engine testing in the 2,000 lbf range and below, which would be satisfied by the ACS, RCL-32 or TS 401. (page 45)

O-5. TS 401 is more suited than ACS to long-duration continuous test runs typical of system-level and qualification/certification testing. (page 50)

O-6. The ACS is more suited than TS 401 to low thrust, component-level development testing not requiring hypergolic propellants. (page 50)

O-7. The NASA FY09 DM assessments indicate the costs are higher for the JSC-WSTF (Bldg 401) at $846,699 compared with the ACS (Bldg 147) at $0. The DM costs for RCL-32 could not be cleanly extracted. (page 55)

O-8. Rocket test facilities (including RCL-32, ACS and JSC-WSTF 401) have historically had a low utilization rate. (page 57)

O-9. NPD 8081.1 Section 2, paragraph b., second sentence: appears to provide limited applicability (greater than 1,000 lbs of thrust), but then applies to all testing activities regardless of thrust level (assumed to mean planning and approval). (page 61)

9.3 NESC Recommendations

R-1. No action should be taken to demolish or modify the GRC ACS or RCL-32 test facilities until the following actions are addressed. These actions are primarily directed to the RPT Program:

R-1a. Re-evaluate the risk of eliminating this capability by performing an assessment of Agency and national needs for current and projected propulsion testing of cryogenic propellant engines and components in the 2000 pound and less thrust range. Then assess domestic testing capabilities in that range (i.e. NASA Centers, Arnold Engineering Development Center, Air Force Research Laboratory, etc). ***(F-4, F-5, F-6, F-7, O-4, O-8)***

R-1b. Based on the assessment from R-1a, evaluate possible alternatives to demolishing ACS and RCL-32 (e.g. disable, standby, mothball) based on demolition costs versus facility life-cycle costs (construction, maintenance, operation, renovation, etc.). ***(F-3, F-9, F-10, O-1, O-2)***

R-2. Revise NPD 8081.1 to include definitions of critical terms and clarify the scope in Section 2, paragraph b. ***(O-9)***

10.0 Alternate Viewpoints

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

11.0 Other Deliverables

There were no other deliverables during the course of this assessment.

12.0 Lessons Learned

No applicable lessons learned were identified for entry into the NASA Lessons Learned Information System (LLIS).

13.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.

Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the NESC to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

14.0 Acronyms List

AA	Associate Administration
ACS	Altitude Combustion Stand
AEDC	Arnold Engineering Development Center
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AJ	Aerojet
APSTB	Auxiliary Propulsion System Test Bed
CCD	Charge Couple Device

CoF	Construction of Facilities
CPIAC	Chemical Propulsion Information Analysis Center
CSG	Chemical Steam Generators
CxP	Constellation Program
DACS	Data Acquisition and Control System
DM	Deferred Maintenance
ESMD	Exploration Systems Mission Directorate
FY	Fiscal Year
GN2	Gaseous Nitrogen
GRC	Glenn Research Center
H2	Hydrogen
HMI	Human Machine Interface
HSFC	Human Space Flight Capability Forum
IPAO	Independent Program Assessment Office
JSC	Johnson Space Center
Kft	thousand feet
KSC	Kennedy Space Center
LaRC	Langley Research Center
LASS	Large Altitude Steam System
LCH4	Liquid Methane
LO2	Liquid Oxygen
MMH	Monomethylhydrazine
MR	mixture ratio
MSFC	Marshall Space Flight Center
N2O4	Dinitrogen Tetroxide
NEC	National Electric Code
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
O&M	Operations and Maintenance
O2	Oxygen
PCAD	Propulsion and Cryogenic Advanced Development (Cx)
PCFS	Propellant Conditioning and Feed Systems
PLC	Programmable Logic Controller
PPBE	Program Planning Budget Execution
Psia	pounds per square inch absolute
Psid	pound per square inch differential
Psig	pounds per square inch gage
QD	Quantity-Distance
RCE	Reaction Control Engine
RCL	Research Combustion Laboratory
ROM	Rough order of Magnitude
RPT	Rocket Propulsion Test

RTD	Resistive Temperature Devices
SASS	Small Altitude Steam System
Scfm	standard cubic feet per minute
SLR	Single-lens Reflex
SOMD	Space Operations Mission Directorate
SSP	Space Shuttle Program
TCB	Transitions Control Board
TRL	Technology Readiness Level
TS	Test Stand
US	United States
WSTF	White Sands Test Facility

15.0 References

1. NPD 8081.1 NASA Chemical Rocket Propulsion Testing, Dated February 4, 2010
2. Glenn Research Center Test Facilities Handbook
3. Glenn Research Center Web page: http://facilities.grc.nasa.gov/
4. White Sands Test Facility Web Page: http://www.nasa.gov/centers/wstf/propulsion/index.html
5. Exploration Requirements for Institutional Capabilities (ERIC) Study

   Chemical Propulsion Information Agency (CPIA) Rocket Propulsion Test Facility (RPTF) database: http://www.cpia.jhu.edu/
6. Rocket Propulsion Test Capability Alignment Study, dated June 21, 2007, AEROSPACE REPORT NO. ATR-2007(5175)-2 – only one listed in text.
7. B-Stand Test Facility Relocation Preliminary Engineering Report, September 2000
8. JSC-WSTF Drawing Numbers: 4296-4 and 4445, 400 Area Site Layout Explosive Quantity Distances
9. NASA-TM-X-74335, U.S. Standard Atmosphere, 1976, U.S. Government Printing Office, Washington, D.C., 1976

Volume II: Appendices (Stand Alone Volume)

Appendix A. Identification of White Sands Test Facility (WSTF) Technical Capability Forward Plan Operations, dated July 16, 2002

Appendix B. White Sands Test Facility "Right Size" - Phase 1, Dated September 3, 2009

Appendix C White Sands Test Facility "Right Size" - Phase 1 Update and Phase II Outbrief, dated December 8, 2009

Appendix D. White Sands Test Facility "Right Size" - WSTF PRG Guidance and Center Director Feedback, dated January 29, 2010

Appendix E. SOMD PPBE 2012 PRG – Final, dated May 7, 2010

Appendix F. GRC Issue Paper – White Sands Test Facility (WSTF Decision Package) – SOMD PRG, date June 4, 2010

Appendix G. White Sands Test Facility Capability Review, TCB-07-03072007, dated August 28, 2007

Appendix H. Propulsion Risk Reduction Activities for Non-Toxic Cryogenic Propulsion Overview, presented at the AIAA Space 2010 Conference

Appendix I. Propulsion & Cryogenic Advanced Development Project Transition Review with the Exploration Technology Development Program (ETDP)

Appendix J. National Altitude Propulsion Testing Facilities Listing

Appendix K. ACS LO2 & Methane Propellant Conditioning System Siting and Quantity Distance Estimates

Appendix L. Altitude Combustion Stand Independent Review - Independent Cost Assessment

Appendix M. Stakeholder Outbrief Presentation